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## Permeable Reactive Treatment (PeRT) Wall

### Results of Field Treatability Studies for the Monticello, Utah, PeRT Wall

November 1998

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RESULTS OF FIELD TREATABILITY STUDIES FOR THE  
MONTICELLO PeRT WALL 11/98



U.S. Department  
of Energy

GRAND JUNCTION OFFICE

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# **Permeable Reactive Treatment (PeRT) Wall**

## **Results of Field Treatability Studies for the Monticello, Utah, PeRT Wall**

November 1998

Prepared by  
U.S. Department of Energy  
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## I. Introduction

A Permeable Reactive Treatment (PeRT) wall is an engineered, subsurface zone of reactive material that treats contaminated groundwater flowing through it. PeRT walls do not require active pumping to extract groundwater but rather rely on the natural flow through the barrier. For PeRT walls to be cost effective, reactive materials must be used that are able to efficiently degrade or sequester the regulated contaminants and that will remain effective over long periods of time. The use of PeRT walls to treat contaminated groundwater *in situ* is emerging as one of the leading innovative technologies for cleaning up contaminated U.S. Department of Energy (DOE) sites because the technology is less expensive to operate, more acceptable to the public, and poses less risk to workers than other methods such as pump and treat.

A large variety of reactive materials were previously evaluated for use in the Monticello PeRT wall in a laboratory study (DOE 1998). The laboratory tests included materials that removed contaminants by sorption, substitution, and reductive precipitation. Based on the test results and the availability and cost of industrial quantities of the materials, it was recommended that zero-valent iron (ZVI) be used in the PeRT wall. Thus, the field treatability studies used only ZVI. ZVI is a scrap material produced in metal machining and is available from several industrial suppliers.

Field treatability experiments were conducted from June 9 through August 19, 1998. The PeRT wall project is funded by DOE's Accelerated Site Technology Deployment Program within the Office of Science and Technology (EM50). The field treatability study was conducted by MACTEC-ERS under contract to the U.S. Department of Energy's (DOE's) Grand Junction Office (GJO). The purpose of the field treatability study is to provide supplemental data that could be used to better predict the effects of emplacing the PeRT wall. The experiments were conducted at the field site so that the conditions would be as similar to those in the PeRT wall as possible. The columns used were much larger than those used in the laboratory investigation to minimize wall effects and to provide larger samples for more detailed analyses. Specifically, the following aspects of the groundwater treatment chemistry were investigated: (1) the ability of five commercial varieties of ZVI to remove contaminants from groundwater; (2) effects of PeRT wall effluent on chemical transport in the downgradient aquifer; (3) the concentrations of Fe and Mn mobilized from the PeRT Wall, and methods that could be employed to control the releases; (4) loss of hydraulic conductivity during the reaction of groundwater with ZVI, (5) potential for release of any of the Priority Pollutants, and (6) determination of the rates of contaminant uptake and mineral precipitation by ZVI. Geochemical modeling was used to help understand the chemical mechanisms responsible for the observed changes in groundwater chemistry.

## II. Background

PeRT walls have been installed as the final remedy to groundwater contamination and have met with regulatory approval at 18 sites. The PeRT walls at these sites are currently treating groundwater to the regulated concentration levels. Management at over 30 other sites is actively pursuing PeRT wall technology and many projects are in the field demonstration phase. The high level of interest in PeRT walls, considering that the first one was installed only 7 years ago, is testimony to the optimism of site managers for the benefits of this technology.

Most PeRT wall projects have targeted halogenated hydrocarbon contaminants with ZVI as the reactive media. Halogenated hydrocarbons are chemically reduced to harmless concentrations of

dehalogenated aliphatics by the ZVI. In contrast, metals and radionuclides are extracted from groundwater and sequestered by reactive materials, but not degraded (some metals like chromium can change oxidation state to a less toxic state but the metal, and the potential for reoxidation, remains).

The preliminary remediation goals (PRG) established for the groundwater at Monticello are listed in Table 1. Contaminants analyzed during this investigation are arsenic (As), chromium (Cr), lead-210 ( $^{210}\text{Pb}$ ), manganese (Mn), molybdenum (Mo), nitrate ( $\text{NO}_3^-$ ), selenium (Se), uranium (U), and vanadium (V). Radium-226 was not analyzed because it has been consistently below the PRG at well 88-85, which is close to the proposed PeRT wall (DOE 1998c). The chemical uranium concentration is considered to be a reliable indicator of isotopic concentrations and therefore  $^{234}\text{U}$  and  $^{238}\text{U}$  were not measured.

*Table 1. Preliminary Remediation Goals for Groundwater at the Monticello Site<sup>1</sup>*

Contaminant of Concern	Preliminary Remediation Goal
As	5 to 50 $\mu\text{g/L}$
Mn	0.5 to 7.7 mg/L
Mo	100 $\mu\text{g/L}$
$\text{NO}_3^-$	44 mg/L
Se	10 to 290 $\mu\text{g/L}$
U	44 to 170 $\mu\text{g/L}$
V	8 to 400 $\mu\text{g/L}$
$^{210}\text{Pb}$	0.5 to 8 pCi/L
$^{226}\text{Ra}$	5 to 28 pCi/L
$^{234}\text{U} + ^{238}\text{U}$	30 to 160 pCi/L
Gross Alpha <sup>2</sup>	15 pCi/L
Gross Beta	4 mrem

<sup>1</sup>From DOE 1998b.

<sup>2</sup>The standards for gross alpha include  $^{226}\text{Ra}$  but exclude radon and uranium.

*Chemistry of Reductive Precipitation.* All of the contaminants used in this investigation form insoluble phases under reducing conditions. Original investigations of ZVI focused on its ability to reductively dechlorinate chlorinated aliphatic hydrocarbons such as solvents. However, it is also increasingly recognized for its ability to chemically reduce inorganic constituents.

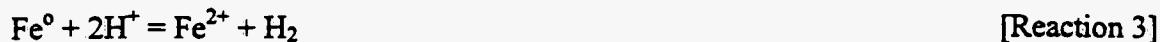
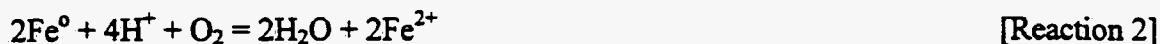
Uranium will precipitate as the mineral uraninite (or an amorphous precursor of this mineral) if the oxidation state of an aqueous solution is lowered sufficiently. As an example of this mechanism that could be useful to PeRT walls, consider the precipitation of uraninite by the oxidation of ZVI to ferrous iron in a U-contaminated, carbonate-bearing, near neutral solution:



Reductive precipitation reactions are generally slower than sorption reactions and seldom reach equilibrium in groundwater systems. All of the contaminants tested in this study are redox sensitive and it was believed that they would precipitate in the presence of ZVI.

Chemical reduction caused by ZVI affects the entire aqueous system and not just the contaminants; some side effects may need to be considered in designing a PeRT wall. As an example, in reaction 1,  $\text{H}^+$  is consumed which leads to an increase in pH. Increases in pH will

lead to precipitation of metal-carbonate or metal-hydroxide minerals that could reduce the permeability of the PeRT wall. The amount of contaminant precipitation due to Reaction 1 is probably small because only trace amounts of U are available even in a contaminated aquifer. However, increases in pH can also occur due to other chemical processes, such as the reduction of dissolved oxygen (Reaction 2) or the direct reduction of aqueous protons (Reaction 3):



Thus, the potential for mineral precipitation due to increasing pH is limited only by the availability of the metals or carbonate and the rates of the reactions. Precipitation of calcite ( $\text{CaCO}_3$ ), siderite ( $\text{FeCO}_3$ ), and ferrous hydroxide [ $\text{Fe(OH)}_2$ ] have been observed in laboratory experiments with ZVI. Generation of hydrogen gas (Reaction 3) has also been observed. Although hydrogen gas is used by some microbes as an electron donor, no detrimental (or positive) effects of hydrogen gas on PeRT walls have yet been confirmed.

### III. Methods

Column experiments were conducted in a field trailer adjacent to well 88-85 from June 9 to July 14, 1998. The trailer was moved to a nearby staging/office area where it was operated from July 14 to August 19, 1998. The move was necessary because of the soil remediation in the area of well 88-85.

Experiments were conducted in 4-foot high, 4-inch (inside) diameter clear acrylic columns. The dry reactive materials were weighed and lightly tamped into the columns. Except in the aeration column, flow was directed from bottom to top, to minimize air entrapment. Master Flex peristaltic pumps were used to pump the liquids. Porosity was calculated from the volume of fluid required to fill the column. Fluid pressures were measured using a gauge at the inflow to each column. Flow rates were determined by measuring the outflow from the column for a period of time at each sampling event. Flow rates typically ranged from about 20 to 80 milliliters (mL) per minute resulting in residence times of about 1 to 4 hours. A complete tabulation of the flow rates and residence times is provided in the appendices. One column was fitted with septa at various positions along the flow path. Water in this column was sampled by inserting a hypodermic syringe needle through the septa.

The aeration column was filled with sieved (3/8 inch) gravel and an aquarium pump was used to bubble air upwards through the column at one liter per minute. This was the only column in which the liquid flowed downward. The liquid was pumped out through a Tygon™ tube that was inserted so that its intake was at the bottom of the gravel.

A column packed with alluvial gravel was used to study the transport of Fe and Mn through the aquifer. The aquifer material was obtained from a backhoe trench. This column was packed while the alluvium was wet. It is believed that the wet packing caused shrink cracking and allowed for preferential flow. We packed another column with dry silt loam (Bluff Sand) to investigate the transport through a more characteristic porous medium. Also, for one test, a 1-inch thick section of the Bluff Sand was replaced with Mg peroxide (an oxygen-release compound obtained from Regenesis, Inc.).

Uranium was analyzed by laser-induced fluorescence (Scintrex UA-3 Uranium Analyzer) in the field and in the GJO Environmental Sciences Laboratory (ESL). This technique responds only to uranium (VI). Uranium was measured by inductively-coupled plasma (ICP) mass spectrometry (MS) in the GJO Analytical Chemistry Laboratory (ACL). ICP/MS responds to all oxidation states of uranium. The differences in U concentrations measured by ICP/MS and laser-induced fluorescence were small indicating that all dissolved U is uranyl ( $U^{+6}$ ).

Measurements of pH, Eh, and conductivity were made with a YSI Co. Model 3500 meter. Standards were used for daily calibrations. Dissolved oxygen (DO) was measured by preferential membrane diffusion on a YSI Co. Model 55 electrode. Alkalinity was measured by titration with sulfuric acid (Hach Co. Model 16900 titrator).

Total dissolved Fe and ferrous Fe were determined in the field by colorimetry (Hach Co. methods). Analyses for ferrous Fe were usually made within 5 minutes of sample collection and always within 30 minutes. In the ESL, Fe was analyzed by flame atomic absorption.

Samples for analyses in the ACL were preserved as indicated in Table 2. Table 3 indicates the ACL procedure number and analysis techniques.

*Table 2. Preservation Methods*

Analyses	Preservation
As, Ca, Fe, K, Mg, Mn, Mo, Se, U, V	nitric acid, pH <2, cooled
Cl, SO <sub>4</sub>	cooled
NO <sub>3</sub>	Sulfuric acid, pH<2, cooled

*Table 3. ACL Analysis Procedures*

Analytes	Procedure No.	Analysis Method
As, Ca, Fe, K, Mg, Mn, Na, Se, V	AS-5 R05	ICP atomic emission spectroscopy
Cl, NO <sub>3</sub> , SO <sub>4</sub>	D-3 R13	Ion chromatography
Mo, U	AS-6 R06	ICP/MS

#### IV. Removal of Contaminants by Five Brands of Zero-Valent Iron

*Objective:* The objective of the tests in Section IV was to compare the performance of five different samples of ZVI for removing contaminants from groundwater.

*Description of Work:* Four companies supplied ZVI for the study: (1) Cercona of America, Inc., Dayton, OH, (2) Connelly GPM, Inc., Chicago, IL, (3) Master Builders, Inc., Cleveland, OH, and (4) Peerless Metal Powders & Abrasive, Detroit, MI. Information about the 5 samples is provided in Table 4. All of the ZVI products are available in commercial quantities. All except the Cercona HSA (high surface area) are byproducts of the automotive industry.

Table 4. Information on ZVI Used in Field Columns

Supplier	Type	Mesh Size <sup>1</sup>	Weight of ZVI (lbs)	Porosity%
Cercona	Cast Fe	-3 +30	45.5	69
Cercona	HSA	-3 +30	44.2	55
Connelly	Cast Fe, 1004	-8 +50	46.7	52
Master Builders	Cast Fe, GX027	-8 +50	40.7	52
Peerless	Cast Fe	-8 +18	36.8	52

<sup>1</sup>Mesh size specified by supplier

Four of the columns were discontinued after about 200 pore volumes. The Peerless column was arbitrarily selected to examine performance over a longer period of 500 pore volumes.

**Results and Discussion:** Raw data for this section are listed in Appendix A. Effluent from all 5 columns maintained a pH of about 7 which is close to the pH of the influent from well 88-85 (Figure 1). This result contrasts with the elevated pH values (up to 11) often observed in treatability studies performed with ZVI at other sites. The pH is apparently buffered by the carbonate system in the Monticello groundwater as discussed in Section X.

The redox state of the effluent from all five columns was significantly lower than in the influent as indicated by lower Eh values (Figure 2) and by lower dissolved oxygen concentrations (Figure 3). An unexplained low Eh anomaly occurs at about 210 pore volumes (Figure 2) which coincides with relocation of the mobile laboratory containing the treatability tests. The relocation was necessary to remediate soil at the site. Effluent concentrations of alkalinity and Ca are lower than in the influent indicating that Ca-carbonate minerals have precipitated in the column (Figures 4 and 5). Sulfate concentration is nearly the same in influent and effluent indicating that sulfate reduction is minimal (Figure 6).

Arsenic, Mo, NO<sub>3</sub>, Se, U, and V concentrations are significantly lower in the effluent than in the influent (Figures 7 through 12). All effluent concentrations were lower than the PRGs (Table 1). Although small differences exist among the different brands of ZVI, all performed nearly the same and all were able to meet the PRG concentration levels.

**Conclusion:** The results from the column experiments indicate that all five brands of ZVI performed nearly the same for reducing contaminant concentrations in the groundwater. Redox state, pH, and major ion chemistry concentrations were also similar among the 5 columns.

## V. Chemical Transport in the Alluvial Aquifer by Effluent from a ZVI-Containing Column

**Objectives:** The objectives of the experiments in this section are: (1) to determine if Fe and Mn in PeRT wall effluents are likely to remain mobile in the alluvial aquifer, and (2) to determine if contaminants are likely to be released from the alluvial aquifer downgradient of the PeRT wall.

**Description of Work:** Alluvial aquifer material was wet packed into a column and the effluent from the Peerless column was passed through it. Concentrations of Fe, Mn, and U were measured on the effluents.

**Results and Discussion:** A red coloration was observed along channels in the alluvial aquifer column indicating that preferential flow paths had developed. These preferential paths are the result of the column having been packed with wet material. The Fe concentration was nearly the same in the influent and effluent of the alluvial aquifer column (Figure 13).

Manganese and U concentrations were significantly higher in the effluent than in the influent indicating that they are added by the alluvial aquifer material (Figures 14 and 15). Manganese and U were released to the alluvial groundwater system during the mill operation. The low redox conditions caused by the ZVI probably provided the chemical conditions suitable for mobilization of Mn from the downgradient alluvium. To mobilize U, the effluent from the ZVI would have to have become more oxidized by contact with the sediments. Concentrations of U decreased as the column was leached. The decrease could be caused by the column becoming reduced by the ZVI effluent or by the depletion of the U inventory. The concentrations are at the lower end of the range of PRGs for Mn and below the range for U (Table 1).

**Conclusions:** Passing effluent from ZVI through a column of alluvial aquifer material did not influence the mobility of Fe. Preferential flow channels that developed during wet packing are probably not characteristic of the in situ aquifer sediment. Because some of the Fe is particulate it is likely that some decrease in concentration will occur as the groundwater flows through the alluvial sediments but the experimental results have not confirmed this. Manganese and U are released from the alluvial sediments by the PeRT wall effluent but at concentrations near or below the low end of the PRG range.

## VI. Iron and Manganese Mobilization from ZVI

**Objectives:** The objectives of the experiments conducted in this section were: (1) to compare the releases of Fe and Mn from the five brands of ZVI, (2) to determine if the Fe or Mn are likely to be removed as the groundwater flows through aquifer sediments, and (3) to determine if the release of Fe and Mn could be reduced through engineering controls.

**Description of Work:** Fe and Mn concentrations were measured in the influent and effluent from the column experiments conducted in Section IV. Effluent from one of the columns (Peerless ZVI) was passed through aquifer material (Section V) and a silt loam (Bluff Sand). The effluent from the Peerless column was also passed through an aeration column and a column containing magnesium peroxide (an oxygen-release compound). Concentrations of Fe and Mn were measured before and after passing through these materials. Concentrations of ferrous and total iron were measured on filtered and unfiltered samples. The raw data from these experiments are provided in Appendix C.

**Results and Discussion:** Dissolved Fe concentrations were higher in the effluents than in the influents indicating that Fe was leached from the ZVI (Figure 16). Fe concentrations varied over time but all 5 brands of ZVI released nearly equivalent amounts. Iron is not a PRG at the site; however, it could be a risk to human health at concentrations over about 9 mg/L. Concentrations of Fe in the effluent ranged from about 10 to 60 mg/L and were typically about 30 mg/L.

Manganese concentrations were also higher in the effluent than in the influent indicating that Mn is leached from the ZVI (Figure 17). The concentrations of Mn are highest in the first samples off the columns indicating that a portion is easily leachable. The concentrations gradually decreased as groundwater flowed through the columns depleting the inventory of leachable Mn.

Although there is some variation in the amount of Mn release among the five brands of ZVI, the relatively small differences may result from different lots of ZVI rather than significant differences among brands. Although Mn is released from the ZVI, the concentrations are below the upper limit of the PRG concentration range (Table 1).

Unfiltered Fe concentrations in the effluents are consistently higher than in filtered samples (Figure 18). Ferrous iron was observed to be the dominant oxidation state in the filtered samples. Flocs of ferric hydroxides probably account for the differences between filtered and unfiltered Fe concentrations. It was hypothesized that particles would be removed (by settling and attachment) from the groundwater as it migrates through the aquifer. In addition, it seemed that the flocculation could be enhanced by oxidizing the groundwater. Experiments were conducted to determine if an engineered oxidation system could reduce the flux of Fe and Mn from the PeRT wall.

Total dissolved Fe concentrations of about 12 to 29 mg/L in the effluent from the Peerless ZVI column were reduced to less than 3 mg/L in an aeration column (Figure 19). The Fe concentrations were reduced to less than 0.2 mg/L when the aerated groundwater passed through the Bluff Sand (Figure 19). Contact with Mg peroxide also caused the Fe concentration to decrease (Figure 19).

In three of the four samples measured, the Mn concentration decreased by aeration (Figure 20). The Mn concentration decreased to less than 0.02 mg/L after passing through the Bluff Sand. This decrease is especially significant because the Bluff Sand releases Mn when contacted by the reducing fluids from the ZVI column without aeration (Figure 20, 400-500 pore volumes). Oxidation by Mg peroxide probably caused the Mn concentration to decrease but the results are inconclusive because of the release from the Bluff Sand.

Increases in the oxidation state resulting from the oxidation treatments are shown in Figure 21. The Eh of the influent to the ZVI column was about 100 mv. The Eh of the effluent from the ZVI column was about -150 mv. The aeration system caused an increase in Eh to about 100 mv. Without aeration, the Bluff Sand caused only a small increase in Eh to about -120 mv. The Mg peroxide treatment caused only a small increase in Eh. The Mg peroxide formed a hard impermeable "puck" which may have caused the groundwater to flow around it. Since Mg peroxide has been used successfully to oxidize the subsurface environment its use should not be rejected without more thorough testing.

*Conclusions:* Groundwater treated by any of the five brands of ZVI will probably contain elevated concentration of Fe and Mn. While it is likely that prolonged flow through the porous media in the aquifer will remove some or all of the Fe and Mn, this was not demonstrated by the experimental results. Oxidizing the groundwater after it exits the PeRT wall will immobilize Fe and probably Mn. Two engineered oxidation systems that could have application to the Monticello PeRT wall project are: an aerated trench, or Mg peroxide placed in downgradient wells.

## VII. Changes in Hydraulic Conductivity

**Objective:** The objective of this portion of the study was to determine if conditions such as mineral precipitation or gas entrapment would cause loss of hydraulic conductivity through a PeRT wall.

**Description of Work:** Pressure was measured at the inflow to each column. An increase in pressure during an experiment is an indication that fluid movement is impeded. The pressure increase should correlate directly to loss of hydraulic conductivity. For example, a doubling of the pressure indicates a halving of hydraulic conductivity. All reported pressures are for a flowing system.

**Results and Discussion:** The initial water pressure ranged between 42 and 50 inches of water (Figure 22). Pressures increased slightly in the Cercona and Connelly columns at about 120 and 200 pore volumes, respectively. All other pressures remained nearly constant for about 200 pore volumes. Nearly every significant increase in pressure is correlated to an experimental event. An increase in pressure from 42 to 85 inches of water occurred at 220 pore volumes after the mobile laboratory was relocated. It is likely that air became entrapped in the lines during the move. After the air was worked out of the lines, the pressure decreased back to about 50 inches of water. At this same time, a column containing alluvial aquifer material was connected in series to the ZVI column. The variation in pressure in the Peerless column after 300 pore volumes is correlated to the operations of columns connected in series with it. When a valve at the outflow of the Peerless column was opened (thus effectively disconnecting the Peerless column from any of the downstream columns), the pressure dropped back to about 60 inches of water.

**Conclusion:** Pressures in the columns remained reasonably stable during the experiments. The maximum increase due to the conditions within the ZVI was from about 42 to 70 inches of water. This is an increase of about 66 percent, which may be caused by mineral precipitation. Alternatively, this increase could have been caused by air entrapment (despite regular attempts to bleed air from the intake lines).

## VIII. Concentrations of Priority Pollutant Metals

**Objective:** The objective of this portion of this study was to determine if any of the priority pollutant metals are likely to be released from ZVI and contaminate the groundwater. This issue was of particular concern after it was discovered that Mn was leached from the ZVI. Since the ZVI is a scrap product from manufacturing processes, it is possible that other metals could also be present.

**Description of Work:** Concentrations of priority pollutant metals were measured on samples collected on July 14, 1998 from each of the columns containing five brands of ZVI. At this time about 200 pore volumes had passed through the columns. Analyses were performed in the Analytical Chemistry Laboratory following standard EPA-approved procedures.

**Results and Discussion:** The concentrations of the priority pollutants are listed in Table 5. Nearly all of the analyses were below the detection limit. Arsenic was above detection but only slightly above the low end of the PRG range; and was much lower than the influent. Two samples had copper concentrations that are slightly above the detection limit.

**Table 5. Concentrations of Priority Pollutant Metals at About 200 Pore Volumes  
(reported in  $\mu\text{g/L}$ )**

	Sb	As	Be	Cd	Cr	Cu	Pb	Hg	Ni	Se	Ag	Th	Zn
<b>Material</b>													
Influent	<1.1	25.5	<1.1	<1.1	<6.7	<5.6	<1.1	<0.2	<18.9	6.7	<1.1	<1.1	<6.7
Cercona cast Fe	2	5.8	<1.1	<1.1	<6.7	6.2	<1.1	<0.2	<18.9	<2.2	<1.1	<1.1	<6.7
Cercona HSA	<1.1	4.8	<1.1	<1.1	<6.7	<5.6	<1.1	<0.2	<18.9	<2.2	<1.1	<1.1	<6.7
Connelly	<1.1	5.2	<1.1	<1.1	<6.7	<5.6	<1.1	<0.2	<18.9	<2.2	<1.1	<1.1	<6.7
Master Builder	<1.1	5.1	<1.1	<1.1	<6.7	7.7	<1.1	<0.2	<18.9	<2.2	<1.1	<1.1	<6.7
Peerless	<1.1	6.3	<1.1	<1.1	<6.7	<5.6	<1.1	<0.2	<18.9	<2.2	<1.1	<1.1	<6.7

*Conclusion:* There does not appear to be any significant release of priority pollutant metals from the ZVI.

## IX. Rates of Contaminant Uptake and Mineral Precipitation

*Objectives:* The objectives of this portion of the study were: (1) to determine how fast the contaminants are removed from the groundwater, and (2) to determine if mineral precipitation will affect PeRT wall longevity. The reaction rates of the contaminants are important considerations in designing the PeRT wall thicknesses. Precipitation of minerals is important in predicting long term performance.

*Description of Work:* Groundwater samples were collected from 11 ports positioned at various depths along a column containing Peerless ZVI. The samples were analyzed for contaminants and major ions. The flow rate ranged from 30.9 to 35.2 and averaged 33.3 mL per minute. The residence time ranged from 2.4 to 2.8 and averaged 2.6 hours.

*Results and Discussion:* The results are tabulated in Appendix D. Contaminant concentration profiles are shown in Figure 23a through 23f. The concentrations of As, U, and V decreased to 4.5, 4.2 and 1.4  $\mu\text{g/L}$ , respectively, before the groundwater reached the first sampling port. The residence time to this port is 6.5 minutes. The concentration of Se decreased to below the detection limit (2.2  $\mu\text{g/L}$ ) by the time the groundwater reached the third port (residence time of 20 minutes). The concentration of Mo and  $\text{NO}_3^-$  decreased more slowly to 16 and 20  $\mu\text{g/L}$ , respectively, by the fifth port (residence time of 42 minutes).

Profiles (not shown) for Na, Mg, K, and Cl showed little variation throughout the column indicating that they have not reacted with the ZVI. Concentrations of Ca decreased gradually suggesting that a Ca-bearing mineral is being precipitated throughout the column (Figure 24a). Apparently the rate of precipitation is slow relative to the groundwater flow so that precipitation does not occur solely at the inlet. Sulfate concentrations decrease a small amount (about 2 percent) suggesting that a small amount of sulfate is being slowly reduced (Figure 24b). The Fe concentration is higher near the inlet end of the column than at the outlet end (Figure 24c). This

could result from a faster corrosion rate due to entrained oxygen. Perhaps ferric colloids formed lower in the column flocculate become immobile as the groundwater moves farther up the column. Manganese concentrations increase steadily from the inlet to the outlet indicating a constant rate of leaching from the ZVI (Figure 24d).

Hydrochloric acid was used to test the ZVI for carbonate minerals after the termination of the experiment. Samples collected along the entire length of the column effervesced. The presence of Ca-Fe carbonate was confirmed by electron microprobe methods (Figure 25). This observation is consistent with the decreasing Ca concentrations observed in the pore fluids (Figure 24a). The Fe contents measured in the carbonate minerals ranged from 26 to 91 atom % with higher Fe contents observed closer to the ZVI surface. The carbonate appears to replace some of the corroded ZVI and it fills some voids. The effect of the carbonate precipitation on hydraulic conductivity is minimized because it is distributed throughout the column rather than all at the inlet.

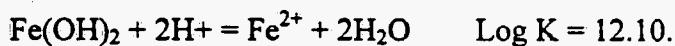
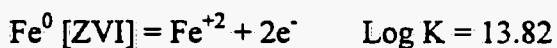
*Conclusions:* Contaminants are immobilized rapidly in the presence of ZVI. The relative reaction rates are in the order U, V > As, Se > Mo, NO<sub>3</sub>. A residence time of 42 minutes is sufficient to immobilize all contaminants and less than 6.5 minutes is required to meet most of the PRGs. Precipitation of Ca-Fe carbonate occurred throughout the ZVI column.

## X. Geochemical Modeling

*Objective:* The objective of the geochemical modeling is to provide a reasonable interpretation of the chemical mechanisms occurring during the interaction of contaminated groundwater with ZVI.

*Description of Work:* The modeling code PHREEQC (Parkhurst 1995) was used to calculate the aqueous concentrations from a variety of possible reaction paths during the interaction of contaminated groundwater with ZVI. The changes in aqueous chemistry observed as contaminated groundwater passed through the Peerless ZVI column were used to validate the reactive geochemical models.

Thermodynamic constants included in the PHREEQC database were used in the calculations. Equilibrium constants for ZVI and crystalline Fe(OH)<sub>2</sub> were needed but were not provided in the PHREEQC database. Therefore, these constants were calculated from free energy data provided in Wagman et al. (1982). The values of the constants are as follows:



All calculations assumed a reaction temperature of 25 degrees C.

Groundwater was first modeled by equilibrating it with ZVI only. Next, it was equilibrated with ZVI while allowing other mineral phases to form. Lastly, the system was modeled by partially equilibrating the groundwater with ZVI and allowing full equilibrium with other mineral phases.

*Results and Discussion:* Significant changes in major ion chemistry that occurred during interaction with ZVI were used to test the validity of geochemical models. Concentrations of C

(estimated from alkalinity) and Ca decreased (Figures 4 and 5), while the concentration of Fe increased (Figure 16). Concentrations of most other major solution parameters (Na, S(VI), Mg, Cl, pH) remained nearly constant and the redox state decreased. The results from the Peerless ZVI column at 50 pore volumes were used for validation. These results are reasonably consistent with results throughout the operation of the column.

Solution parameters calculated by the equilibration of the contaminated groundwater with ZVI are significantly different from observed parameters (Table 6). The calculated pH is high (11.7) due mainly to acid loss through the reduction of aqueous protons. No Ca-carbonate minerals form so Ca and C concentrations remain constant, nearly all sulfate is reduced to sulfide, and the Fe concentration is much higher than observed. Thus, equilibration solely with ZVI does not explain the observed groundwater chemistry.

*Table 6. Calculated Parameters for Equilibration of Influent Groundwater with ZVI (mol/L)*

	pH	PE	Ca	C(IV)	S(VI)	Fe
Influent	7.12	2.88	$8.25 \times 10^{-3}$	$8.59 \times 10^{-3}$	$9.65 \times 10^{-3}$	$1.21 \times 10^{-6}$
Observed Effluent	7.34	-2.64	$5.25 \times 10^{-3}$	$4.44 \times 10^{-3}$	$9.63 \times 10^{-3}$	$4.86 \times 10^{-4}$
Model Effluent	11.7	-9.17	$8.25 \times 10^{-3}$	$8.59 \times 10^{-3}$	$1.34 \times 10^{-6}$	$3.08 \times 10^{-2}$

In the next simulation, the groundwater was equilibrated with ZVI while allowing other mineral phases (calcite,  $\text{Fe(OH)}_2$ ,  $\text{Fe(OH)}_3$ , and gypsum) to precipitate if they reached saturation. Of these, only  $\text{Fe(OH)}_2$  precipitated. The simulation results do not match the observed results (Table 7). The calculated pH is 12.22, the carbonate is all reduced to methane that prevented the formation of calcite, sulfate is nearly all reduced to sulfide, and the Fe concentration is lower than observed. The low Fe concentrations are due to the precipitation of  $\text{Fe(OH)}_2$ . Thus, equilibration with ZVI while allowing other minerals to form does not explain the observed groundwater chemistry.

*Table 7. Calculated Parameters for Equilibration of Influent Groundwater with ZVI (mol/L); Calcite,  $\text{Fe(OH)}_2$ ,  $\text{Fe(OH)}_3$ , and Gypsum Allowed to Form.*

	pH	PE	Ca	C(IV)	S(VI)	Fe
Influent	7.12	2.88	$8.25 \times 10^{-3}$	$8.59 \times 10^{-3}$	$9.65 \times 10^{-3}$	$1.21 \times 10^{-6}$
Observed Effluent	7.34	-2.64	$5.25 \times 10^{-3}$	$4.44 \times 10^{-3}$	$9.63 \times 10^{-3}$	$4.86 \times 10^{-4}$
Model Effluent	12.22	-13.25	$8.25 \times 10^{-3}$	$9.56 \times 10^{-28}$	$4.27 \times 10^{-33}$	$3.41 \times 10^{-8}$

Since ZVI is known to corrode slowly, it may react incompletely as the groundwater flows through the columns. Thus, it is instructive to examine the phase changes that occur as the groundwater proceeds along a reaction path toward equilibration with ZVI (Figure 26). For illustration purposes, the reaction progress is divided into four zones designated by roman numerals. In the early stages, the precipitation of calcite tends to buffer pH of the system (Zones I and II). The dissolution of ZVI causes the reduction of C(IV) and S(VI) producing methane and sulfide in Zones II and III (note that for simplicity only the carbonate system is shown on Figure 26).  $\text{Fe(OH)}_2$  forms early and persists as the reactions progress to ZVI equilibration. The calculated pH is near the observed effluent value only during the early portion of Zone I.

Figure 27 shows the calculated and observed aqueous parameters during the early portion of Zone I. The predicted Ca, C, Fe, and pH values after about 0.002 mol of ZVI have dissolved are reasonably consistent with those observed in the column effluent. However, the model predicts slightly higher concentration of Fe and a slightly lower concentration of Ca. The calculated results agree better if a solid solution of Fe/Ca carbonate is used instead of pure end-member calcite (Figure 28). The presence of Fe/Ca carbonate was confirmed in samples collected throughout the column (Figure 25).

The mineral uraninite ( $\text{UO}_2$ ) precipitates under low redox conditions. As indicated in Figure 29, the predicted U concentration is less than the detection limit (about 1 ug/L) prior to dissolution of 0.002 mol/L of ZVI. Thus, the precipitation of uraninite is compatible with the low observed concentrations of U.

**Conclusions:** Simulated equilibrations of groundwater with ZVI with or without other mineral phases do not match the observed groundwater chemistry. However, simulations using partial equilibration with ZVI accurately match the observed groundwater chemistry. The simulations match observations even more closely if a Fe/Ca carbonate phase is used instead of end-member calcite.

## XI. References

- U.S. Department of Energy, 1998a. *Results of Laboratory Treatability Testing for the Monticello PeRT Wall*, GJO-98-52-TAR, prepared by MACTEC for the U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado.
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- \_\_\_\_\_, 1998c. *Monticello Mill Tailings Site, Operable Unit III, Remedial Investigation*, GJO-97-6-TAR, prepared by MACTEC for the U.S. Department of Energy Grand Junction Office, Grand Junction, Colorado, September.
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- Wagman, D.D., W.H. Evans, V.B. Parker, R.H. Schumm, I. Halow, S.M. Bailey, K.L. Churney, and R.L. Nuttal, 1982. *The NBS Tables of Chemical Thermodynamic Properties Selected Values for Inorganic and C<sub>1</sub> and C<sub>2</sub> Organic Substances in SI Units*, American Chemical Society Journal of Physical and Chemical Reference Data, v. 11, Supplement No. 2, 392 pp.

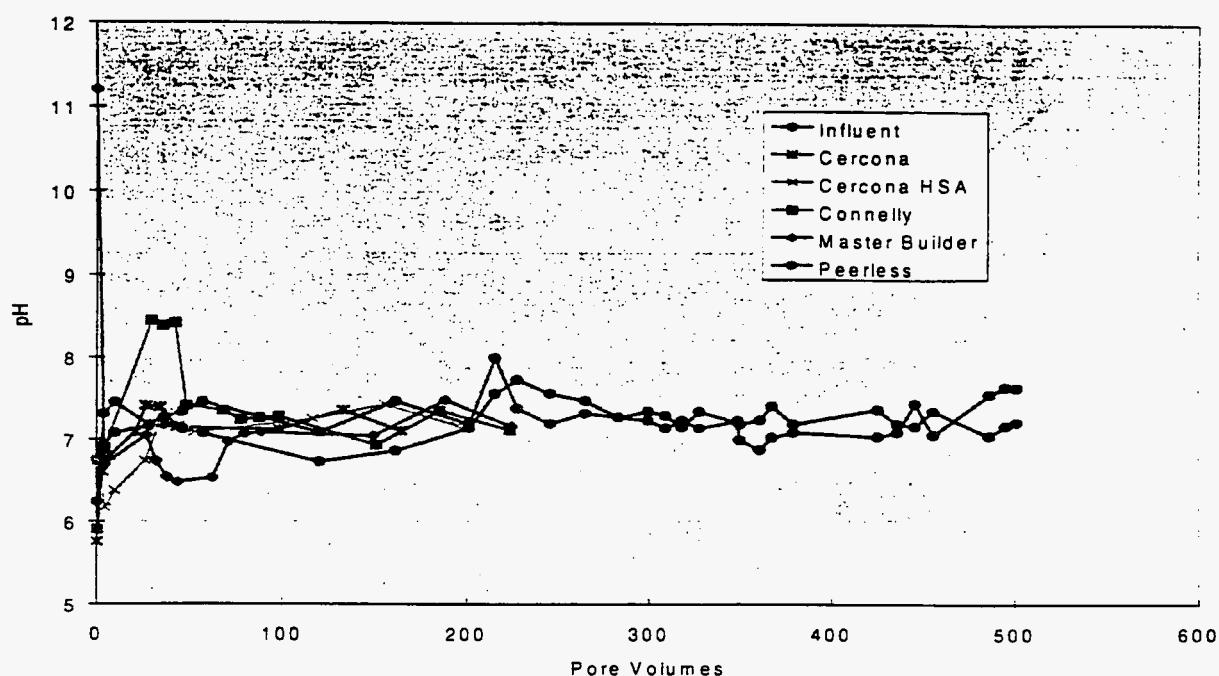


Figure 1. pH in Effluent from Five Columns Containing Different Brands of ZVI

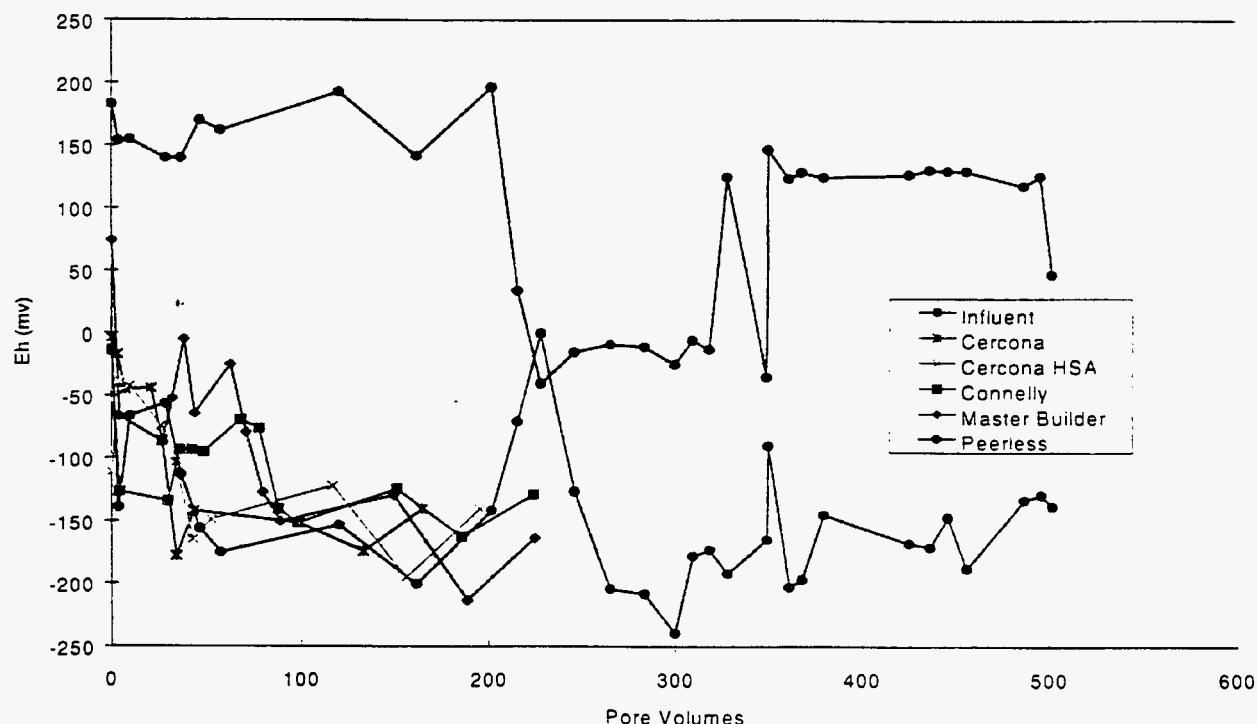


Figure 2. Eh in Effluent from Five Columns Containing Different Brands of ZVI

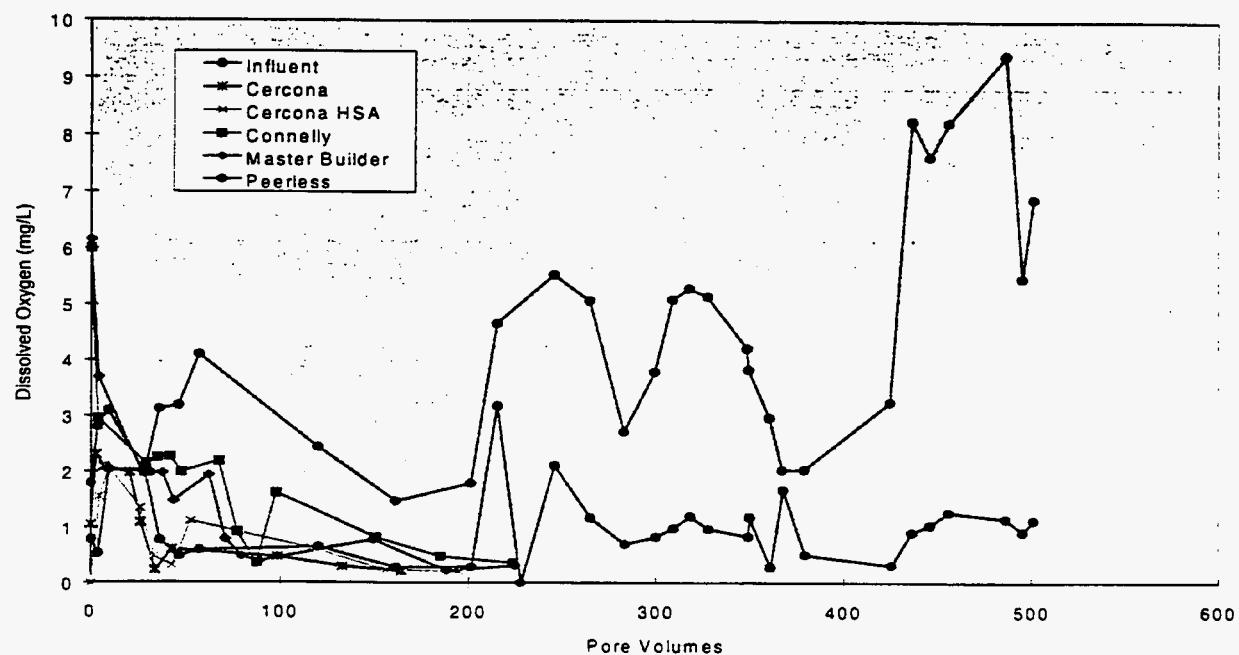


Figure 3. Dissolved Oxygen in Effluent from Five Columns Containing Different Brands of ZVI

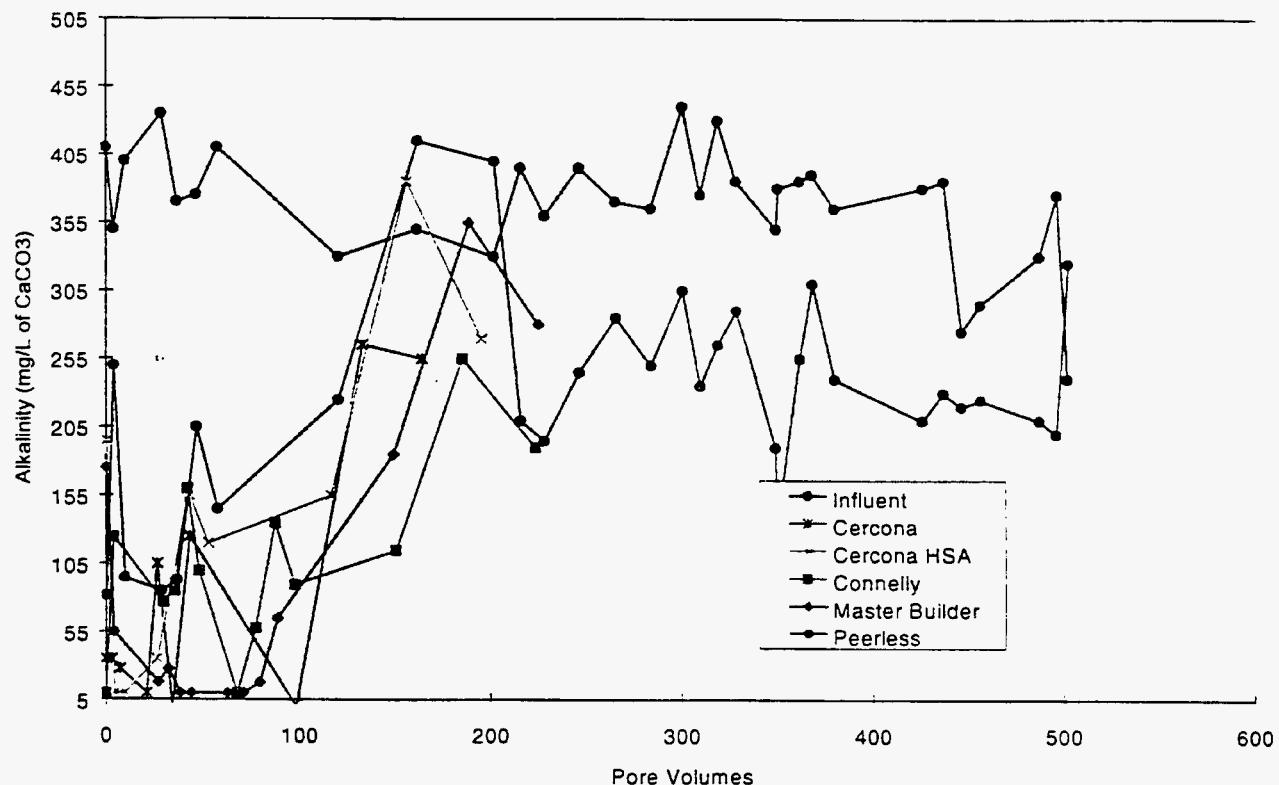


Figure 4. Alkalinity in Effluent from Five Columns Containing Different Brands of ZVI

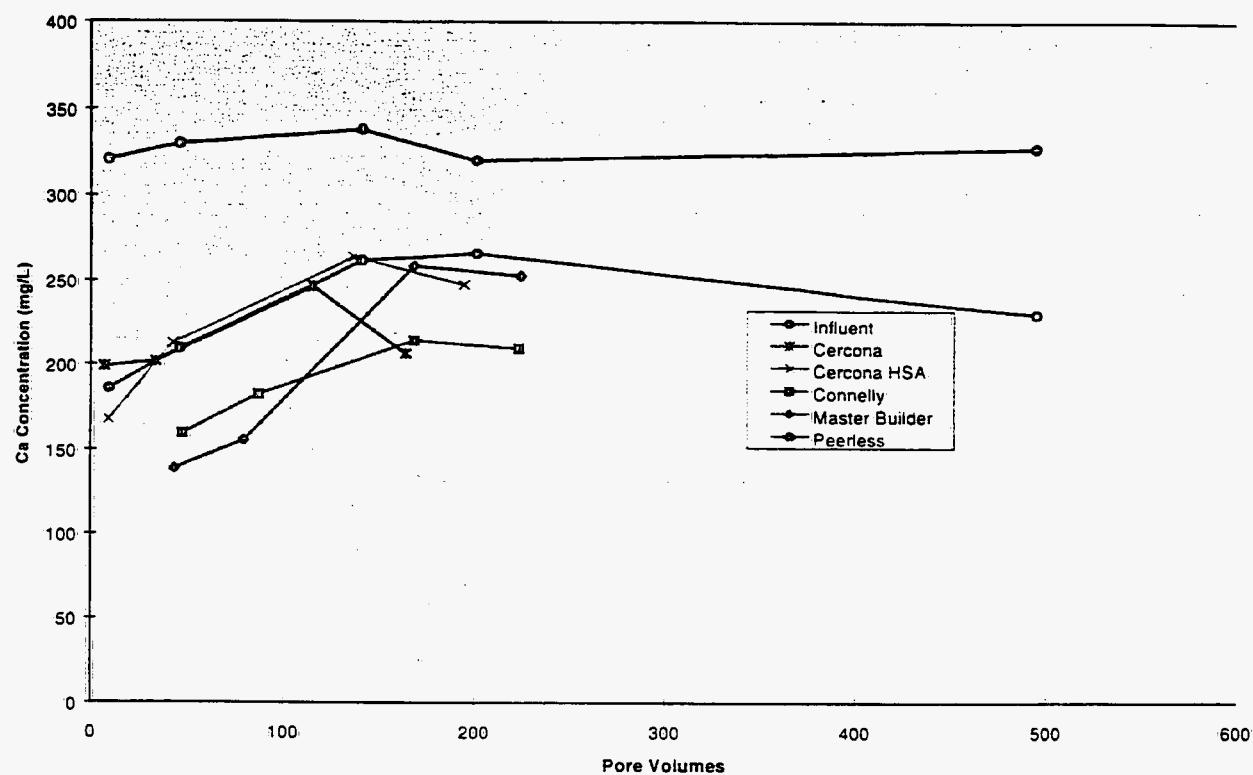


Figure 5. Ca Concentration in Effluent from Five Columns Containing Different Brands of ZVI

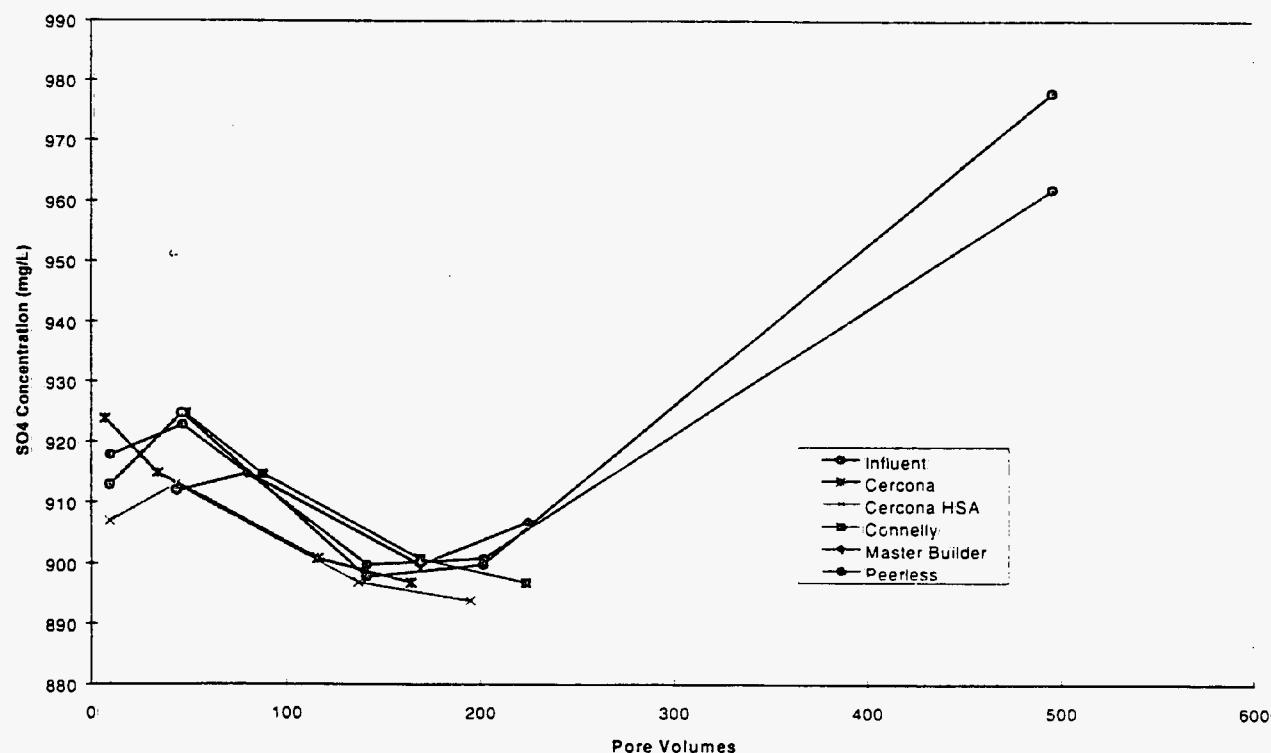


Figure 6. SO<sub>4</sub> Concentration in Effluent from Five Columns Containing Different Brands of ZVI

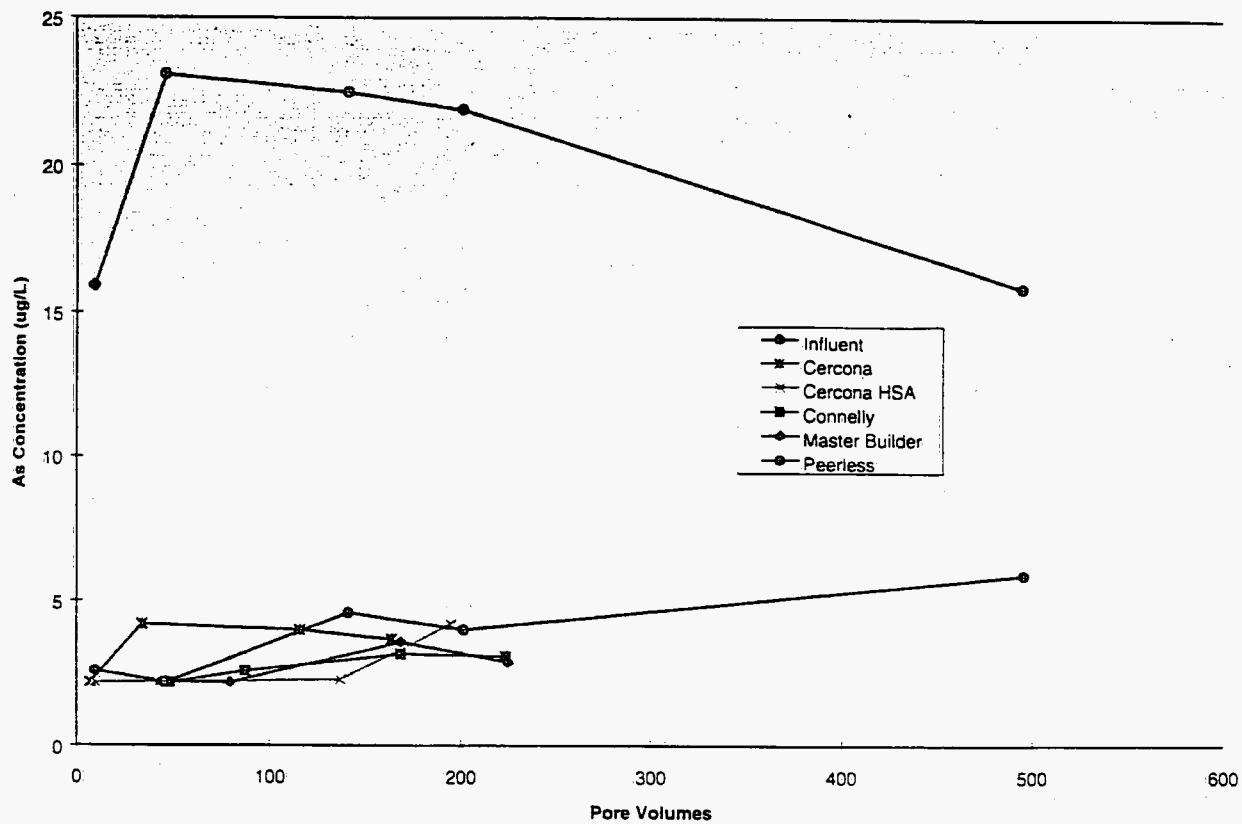


Figure 7. As Concentration in Effluent from Five Columns Containing Different Brands of ZVI

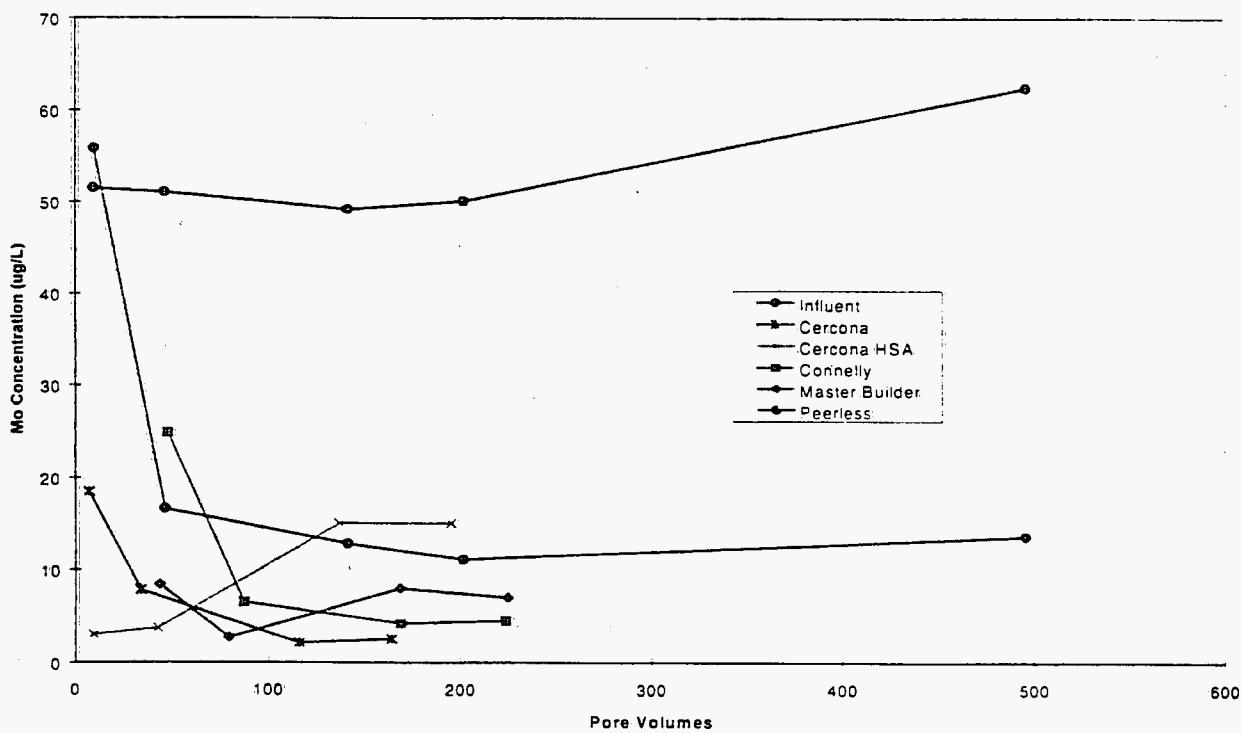


Figure 8. Mo Concentration in Effluent from Five Columns Containing Different Brands of ZVI

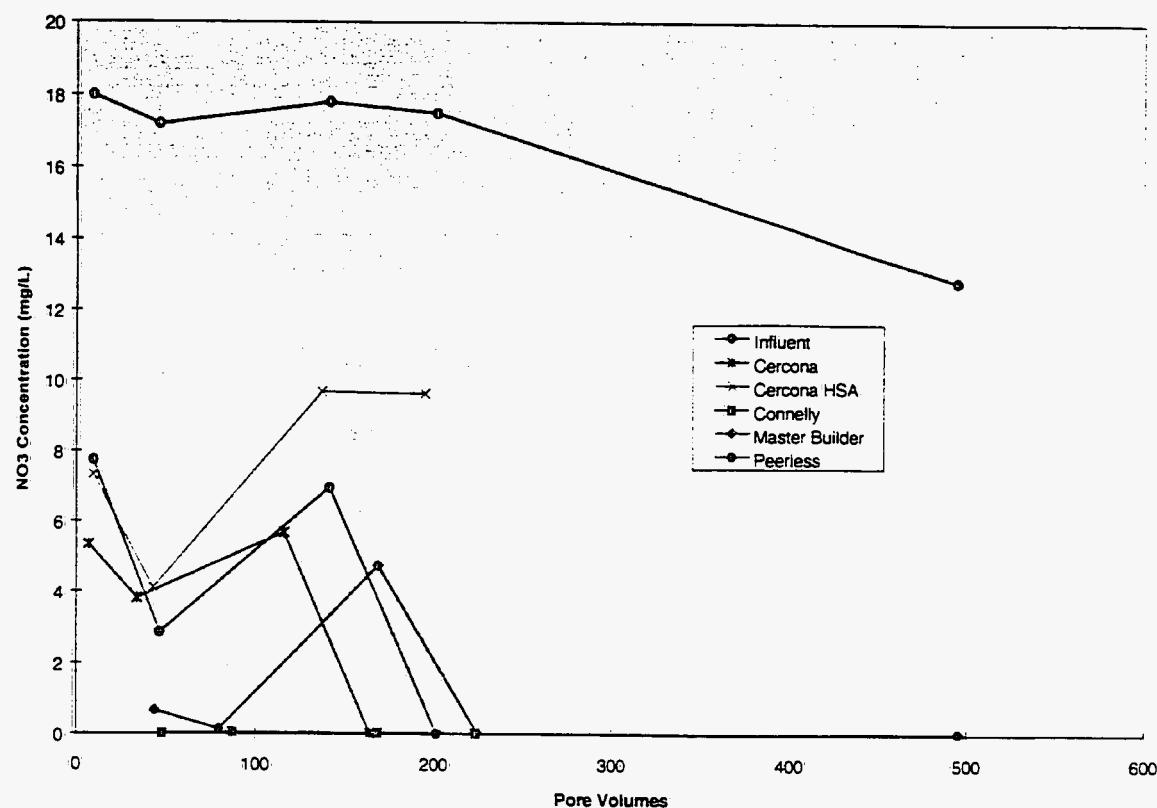


Figure 9. NO<sub>3</sub> Concentration in Effluent from Five Columns Containing Different Brands of ZVI

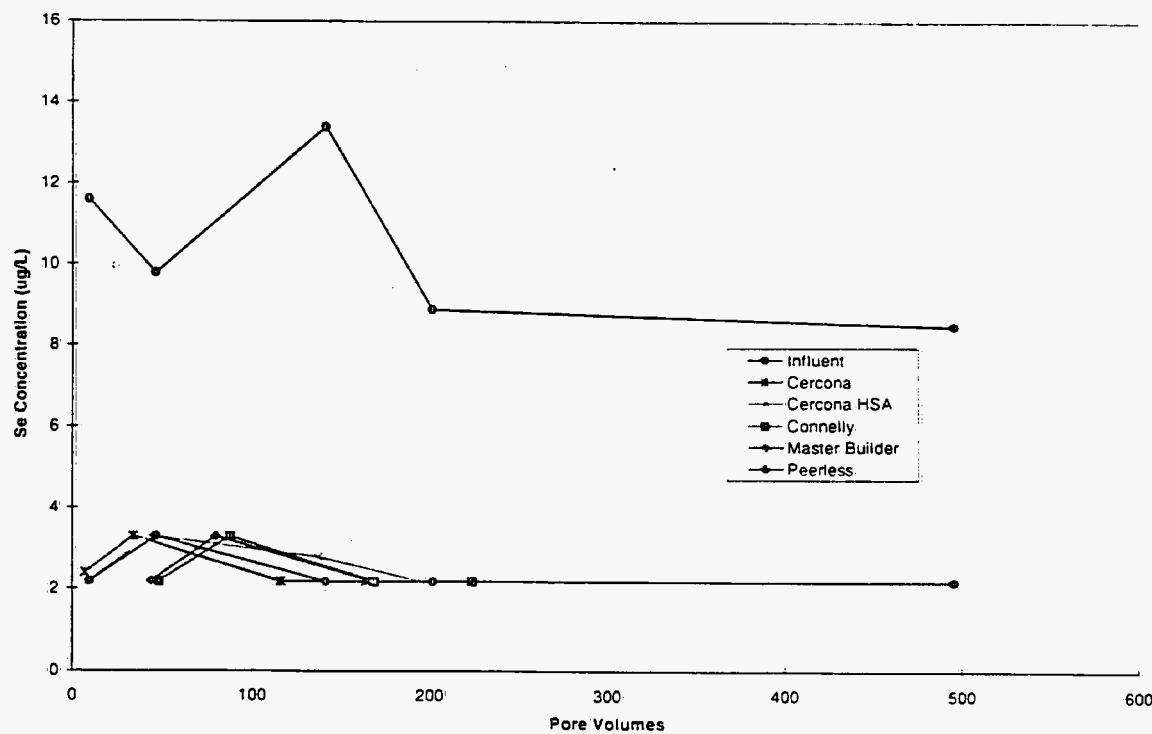


Figure 10. Se Concentration in Effluent from Five Columns Containing Different Brands of ZVI

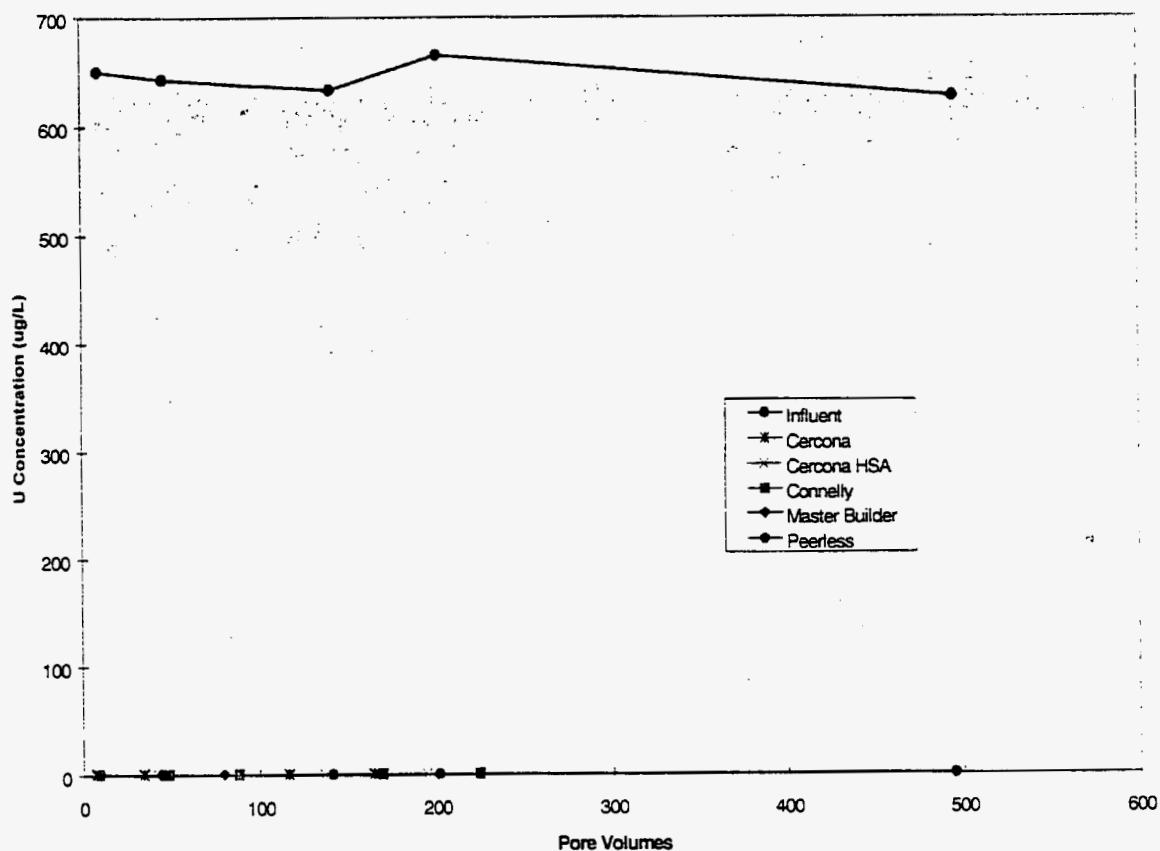


Figure 11. U Concentration in Effluent from Five Columns Containing Different Brands of ZVI

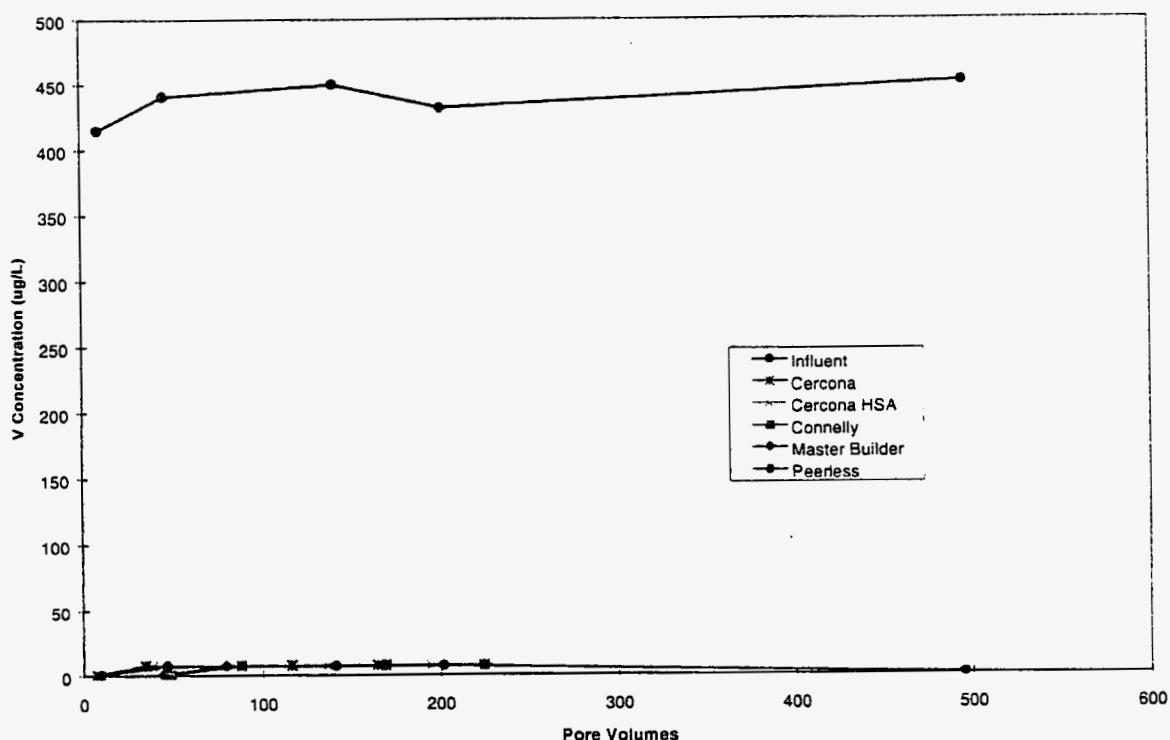


Figure 12. V Concentration in Effluent from Five Columns Containing Different Brands of ZVI

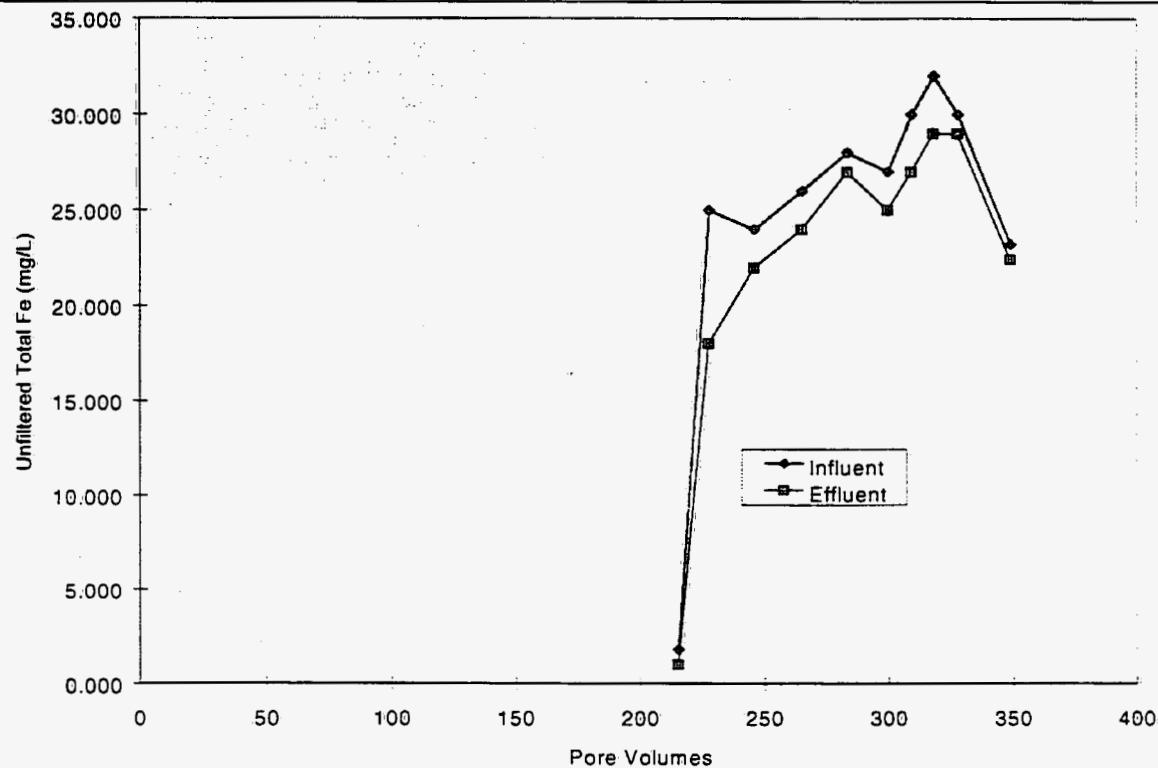


Figure 13. Fe Concentration in Influent and Effluent of the Alluvial Aquifer Column  
The Influent was the Effluent from the Peerless ZVI Column.

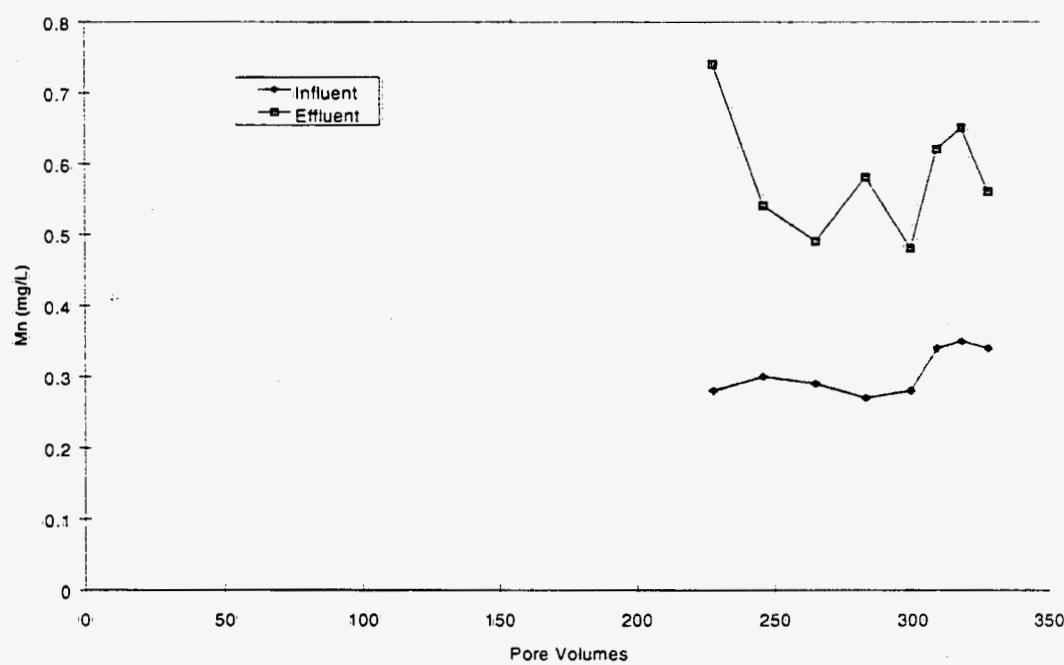


Figure 14. Mn Concentration in Influent and Effluent of the Alluvial Aquifer Column  
The Influent was the Effluent from the Peerless ZVI Column.

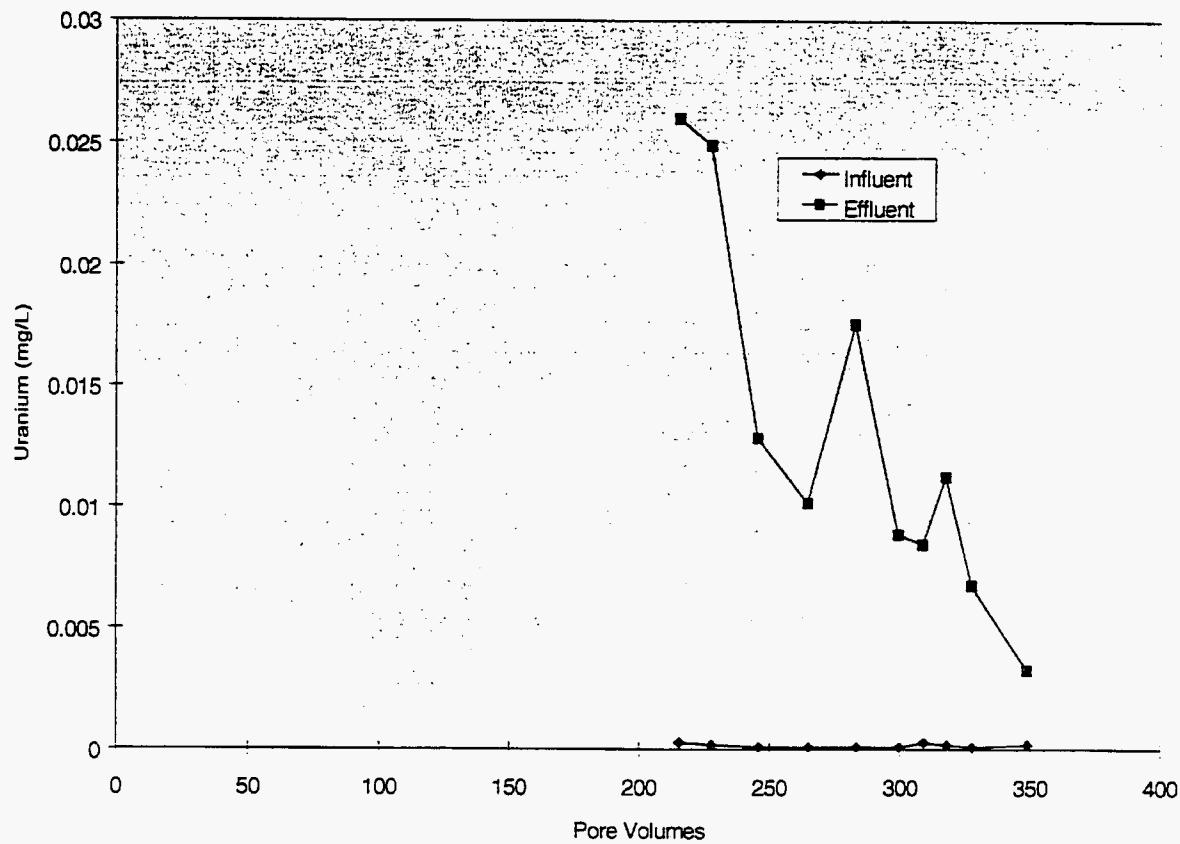


Figure 15. U Concentrations in Influent and Effluent of the Alluvial Aquifer Column.  
The Influent was the Effluent from the Peerless ZVI Column

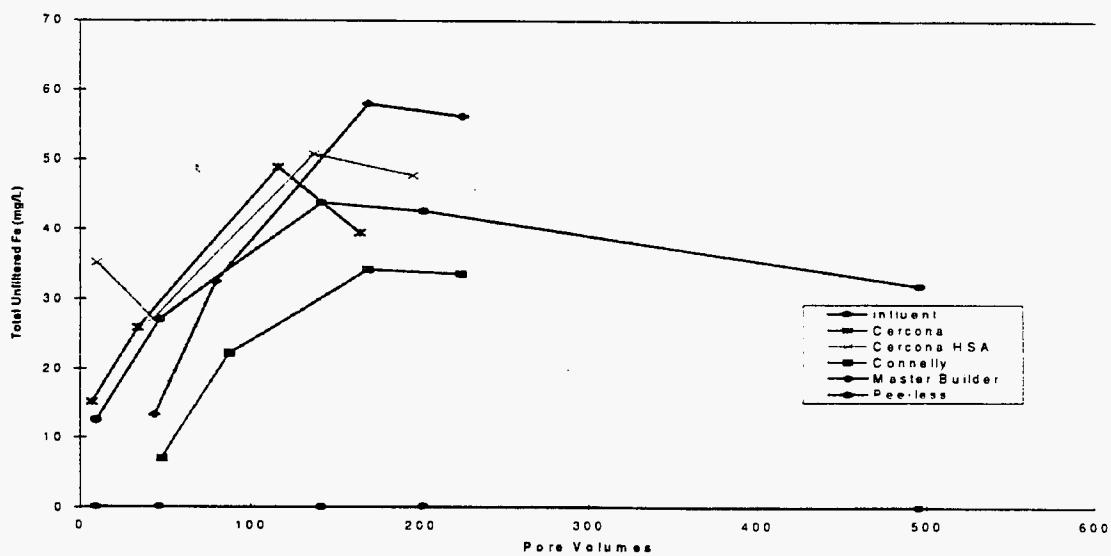


Figure 16. Fe Concentration in Effluent from Columns Containing Five Brands of ZVI

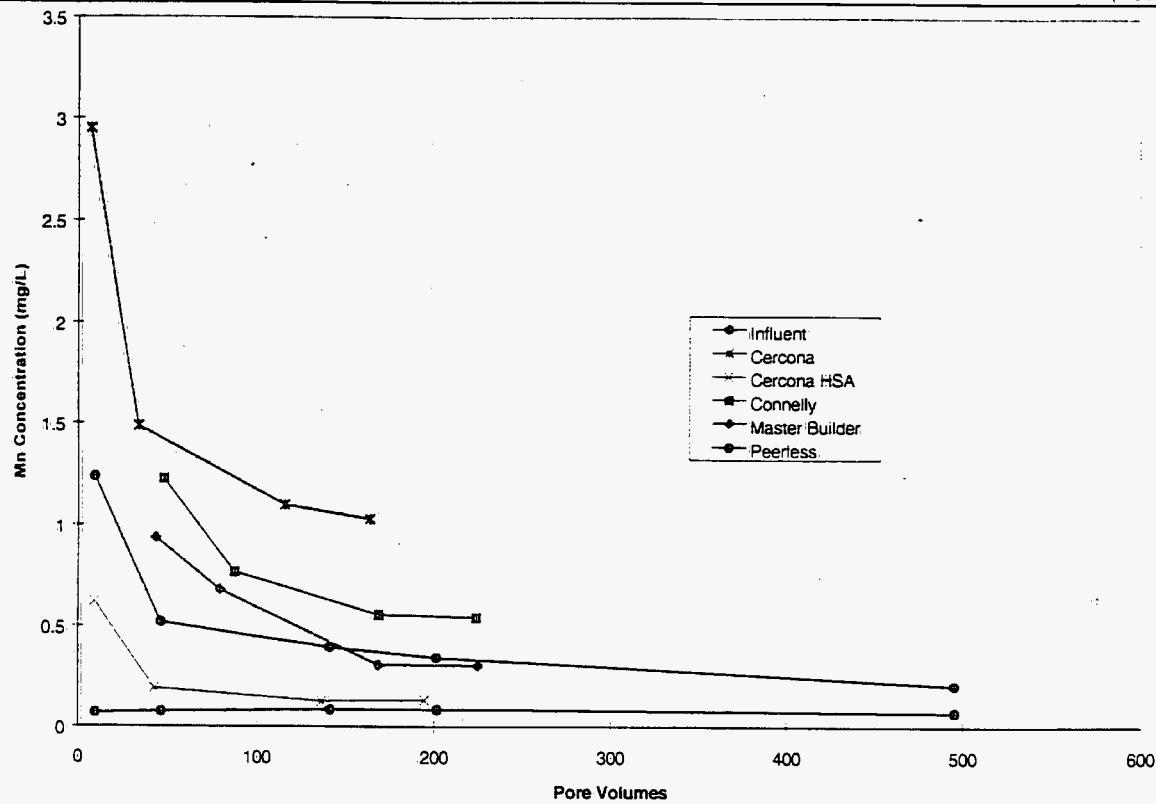


Figure 17. Mn Concentrations in Effluent from Columns Containing Five Brands of ZVI

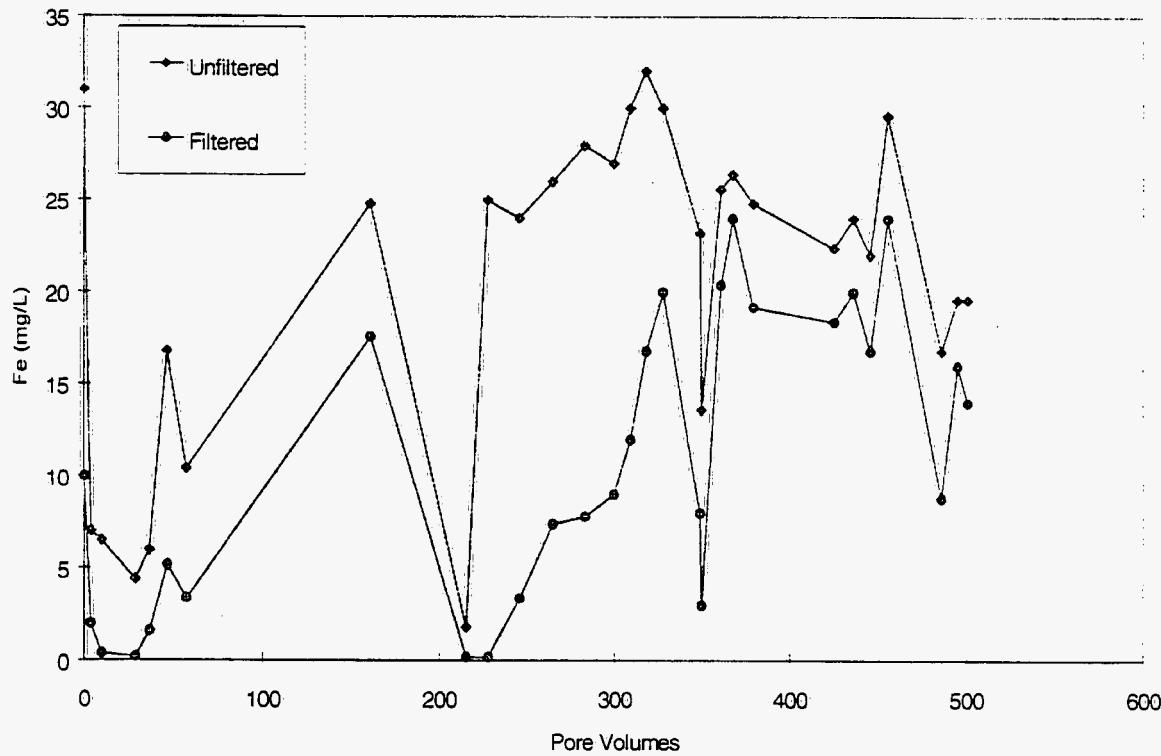
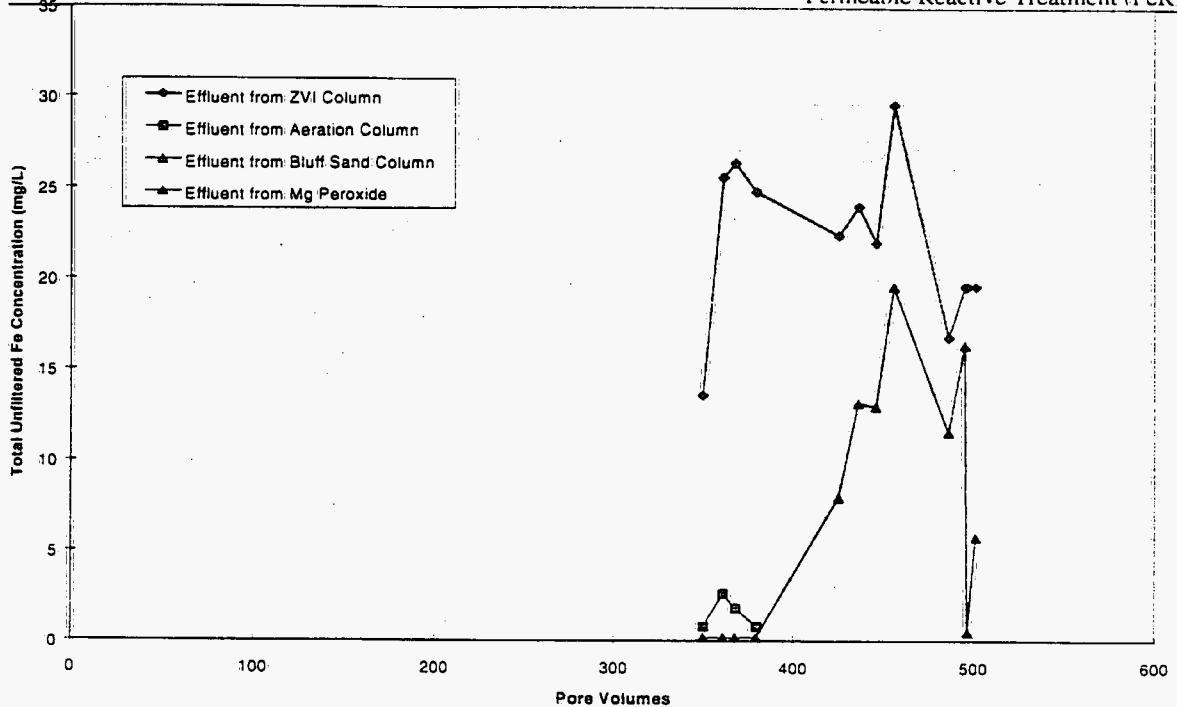
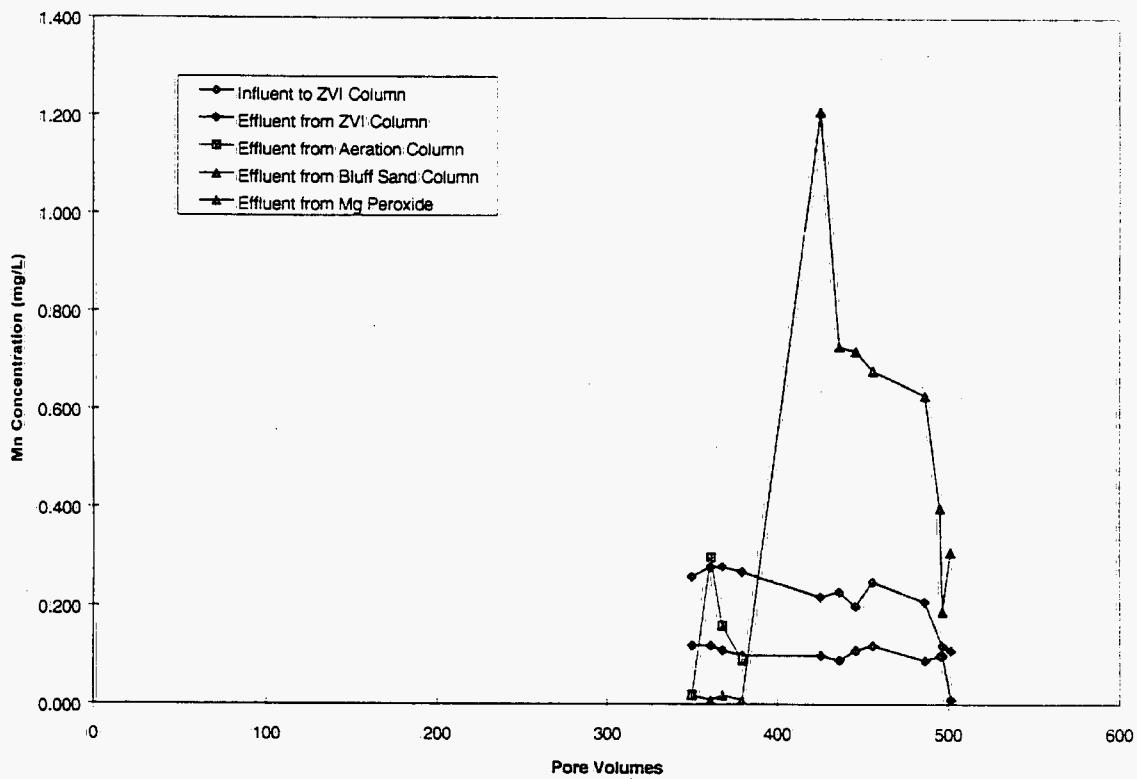


Figure 18. Comparison of Fe Concentrations Between Filtered and Unfiltered Samples of Effluent from Peerless ZVI Column



*Figure 19. Fe Treatment by Oxidation  
Fe Concentrations in Peerless ZVI effluent (Blue), After Aeration (Pink), After Passing Through Silt Loam (Green), and After Passing Through Mg Peroxide (Red).*



*Figure 20. Mn Treatment by Oxidation  
Mn Concentrations in Peerless ZVI Effluent (Blue), After Aeration (Pink), After Passing Through Silt Loam (Green), and After Passing Through Mg Peroxide (Red).*

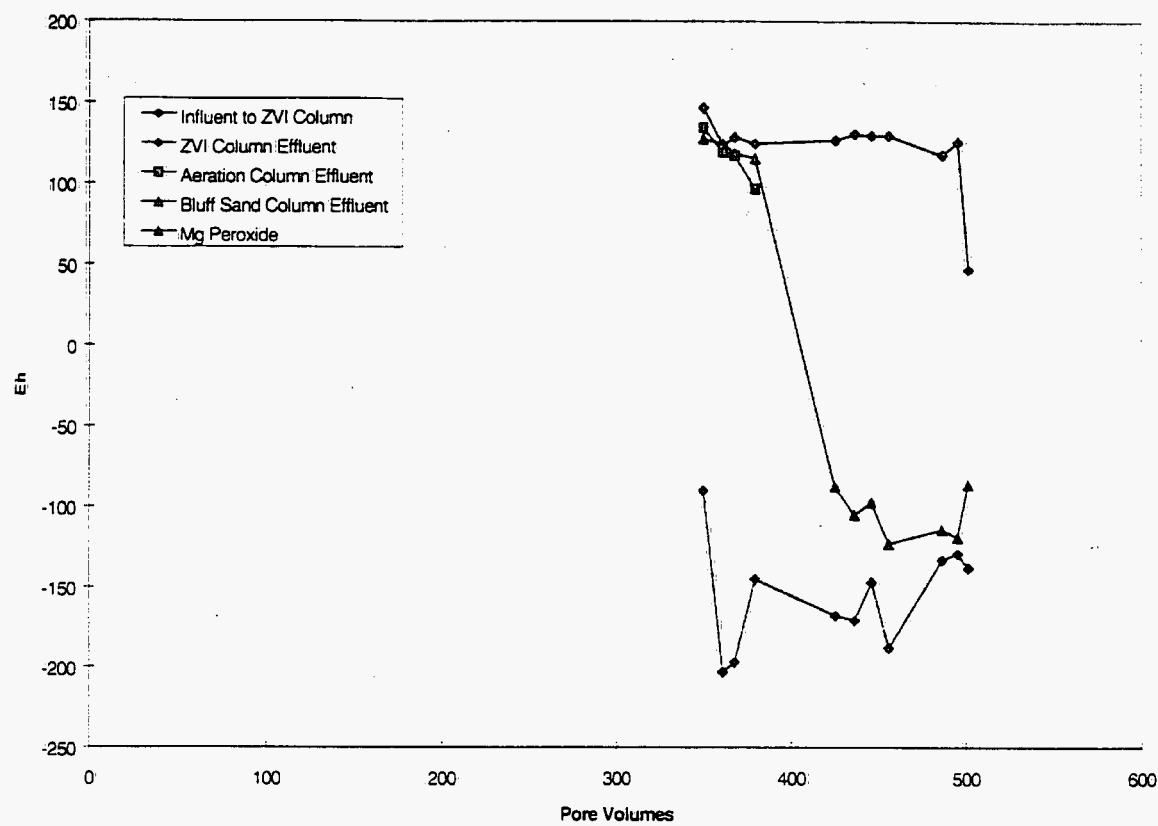


Figure 21. Eh of Groundwater After Oxidation Treatment

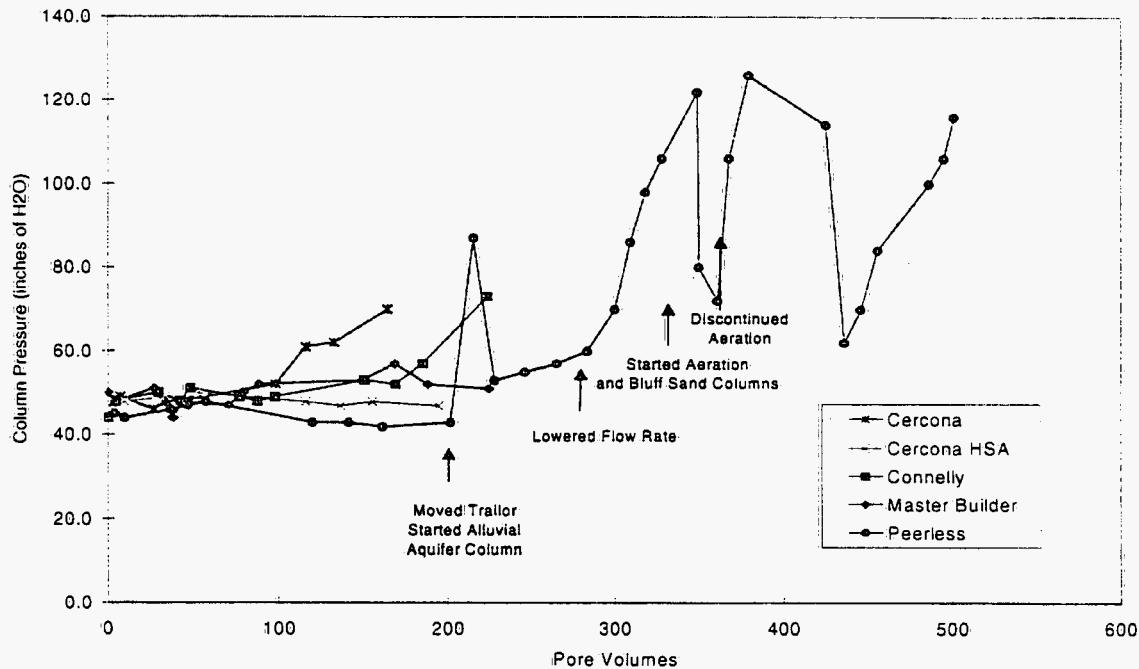


Figure 22. Fluid Pressure at the Inflow to the ZVI Columns

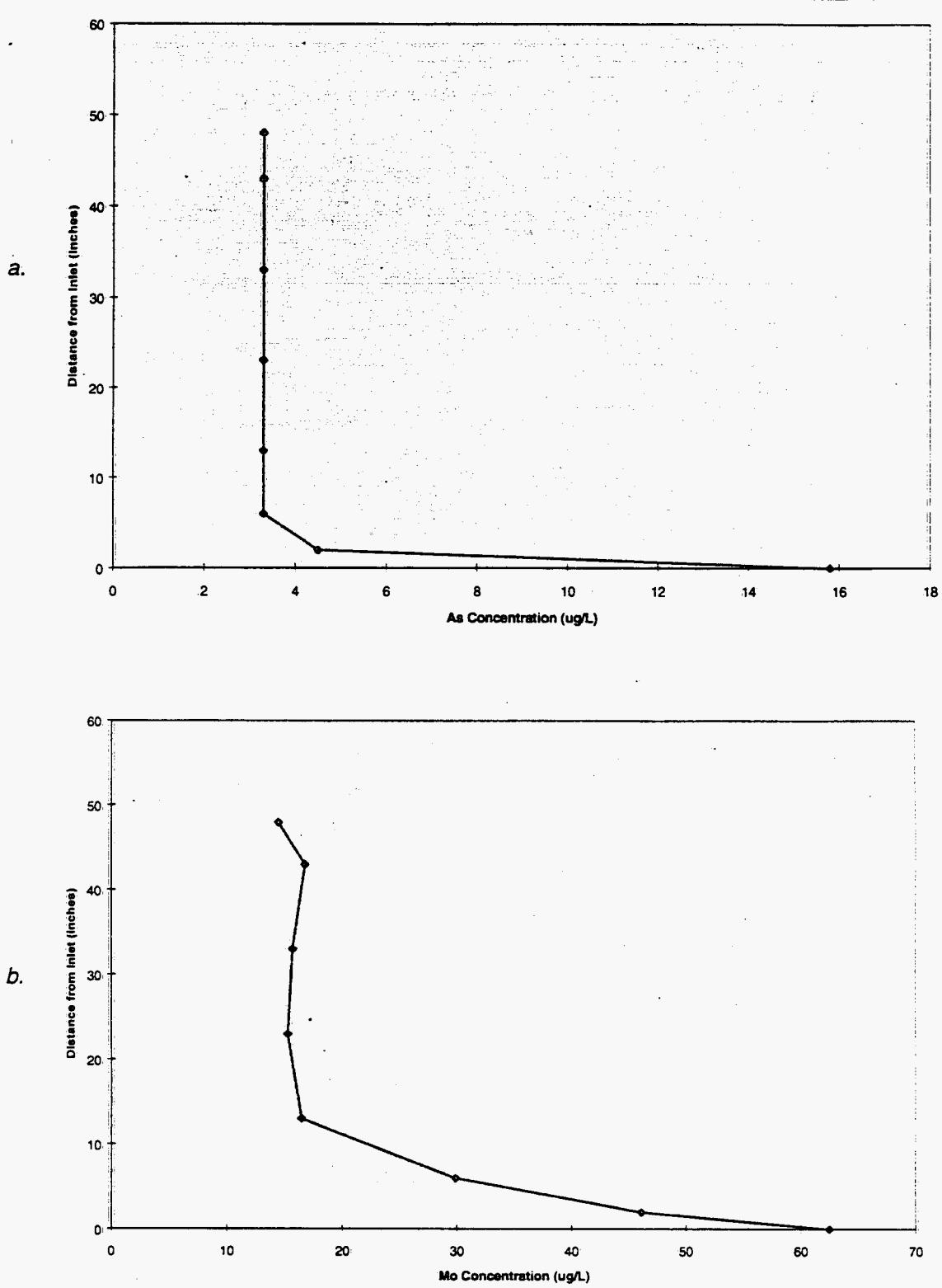


Figure 23. Contaminant Concentration Profiles for the August 19, 1998, Sampling

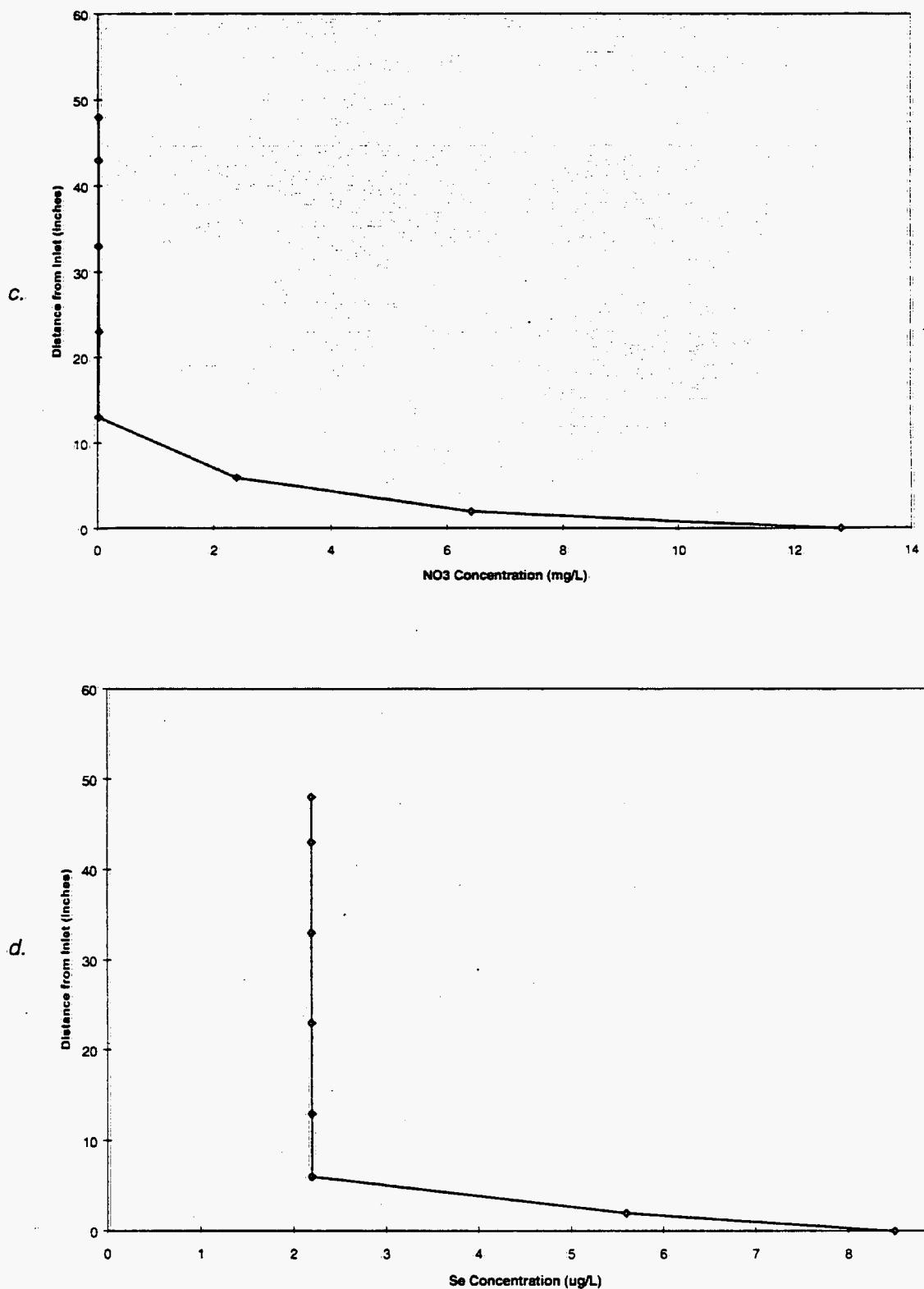


Figure 23 (continued). Contaminant Concentration Profiles for the August 19, 1998, Sampling

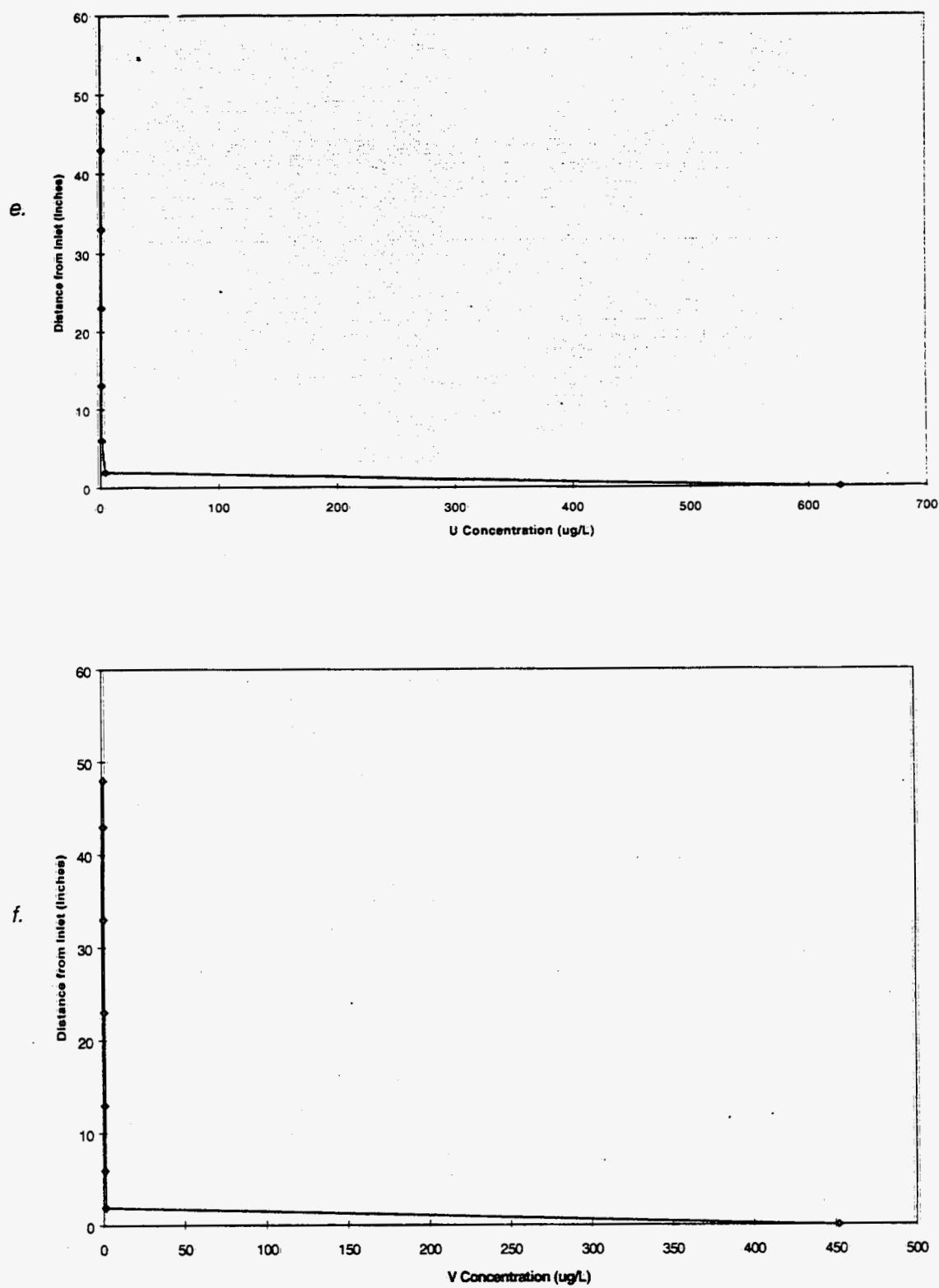


Figure 23 (continued). Contaminant Concentration Profiles for the August 19, 1998, Sampling

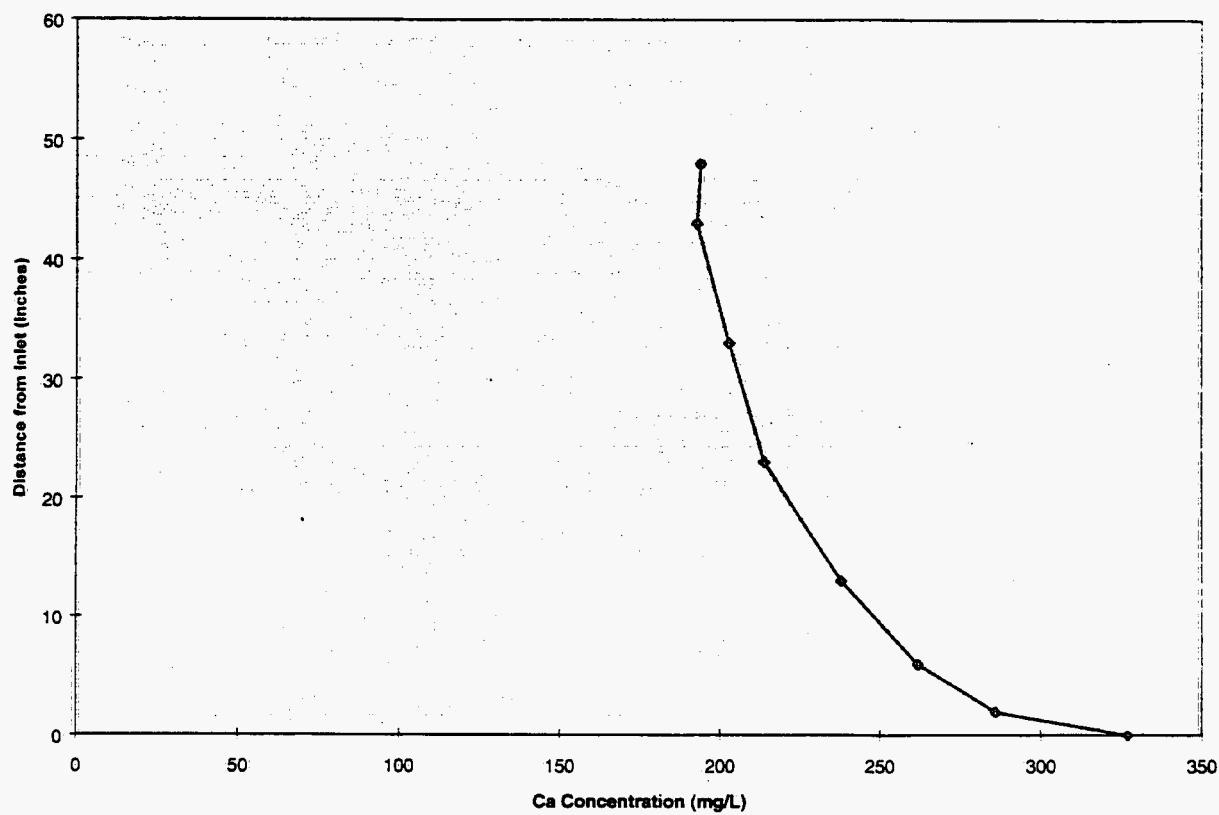
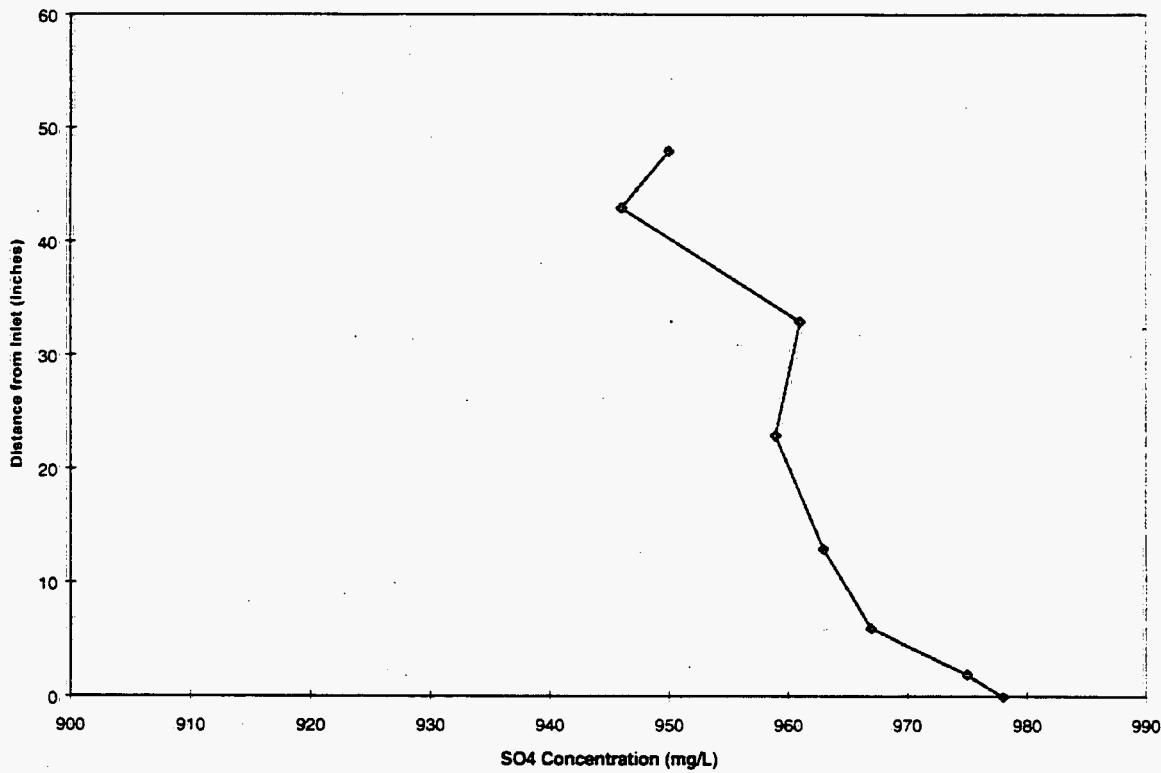
**a.****b.**

Figure 24. Contaminant Concentration Profiles for the August 19, 1998, Sampling

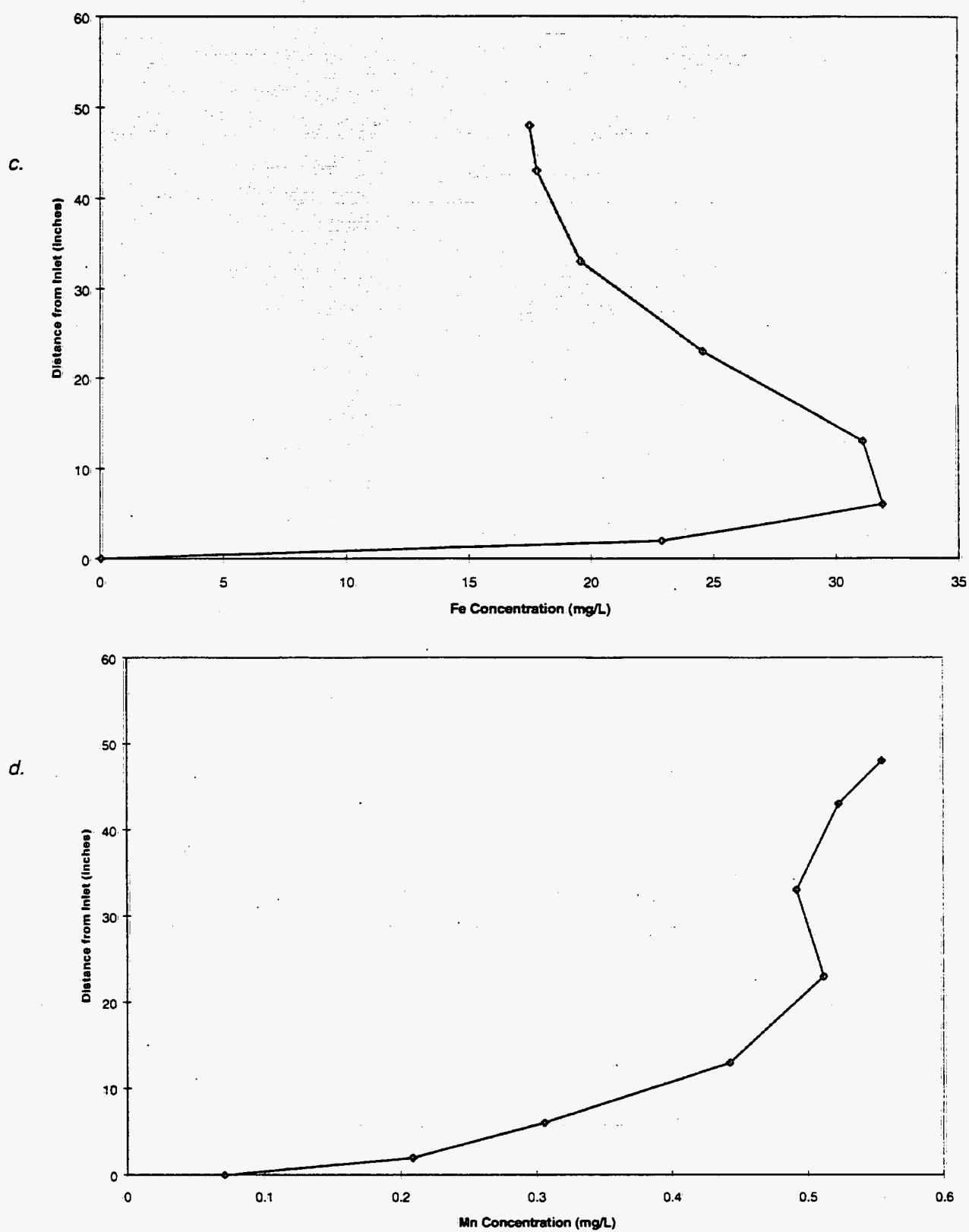


Figure 24 (continued). Contaminant Concentration Profiles for the August 19, 1998, Sampling

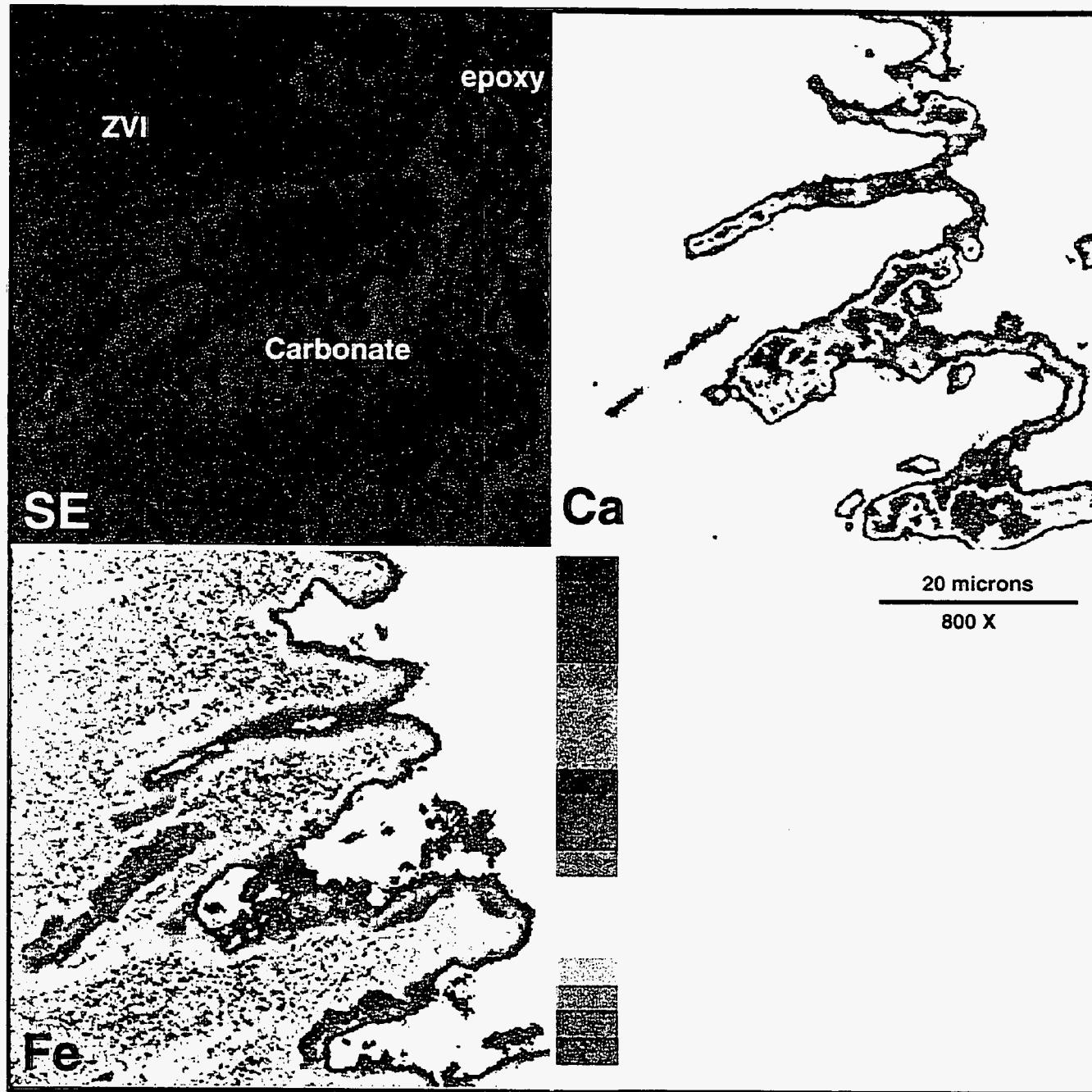


Figure 25. Electron Microprobe Backscatter Electron (SE), Calcium (Ca), and Iron (Fe) Maps of ZVI After Contact with Contaminated Groundwater

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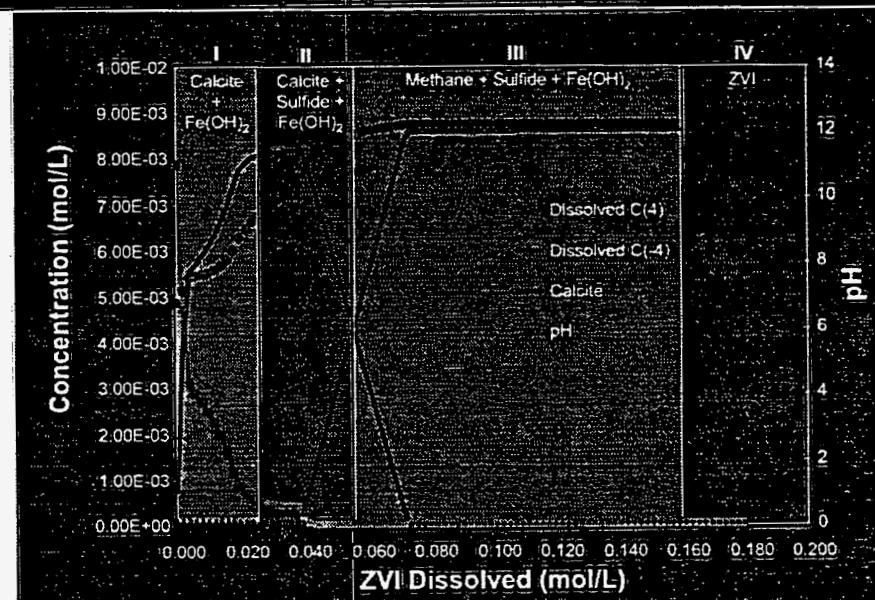


Figure 26. Reaction Path Mineral Zonation and Carbonate Chemistry as Groundwater Proceeds to Equilibrium with ZVI

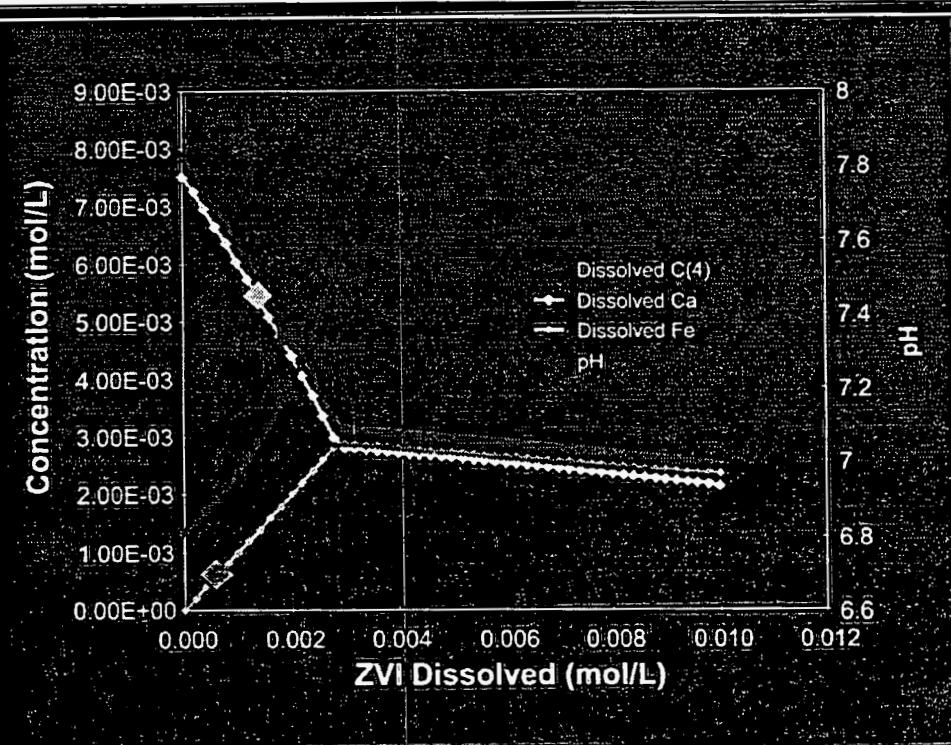


Figure 27. Calculated Reaction Path Chemistry as Groundwater Proceeds to Equilibrium with Zvi,  $\text{Fe}(\text{oh})_2$ , and Calcite Large Symbols Indicate the Values That Were Observed in the Column Effluents.

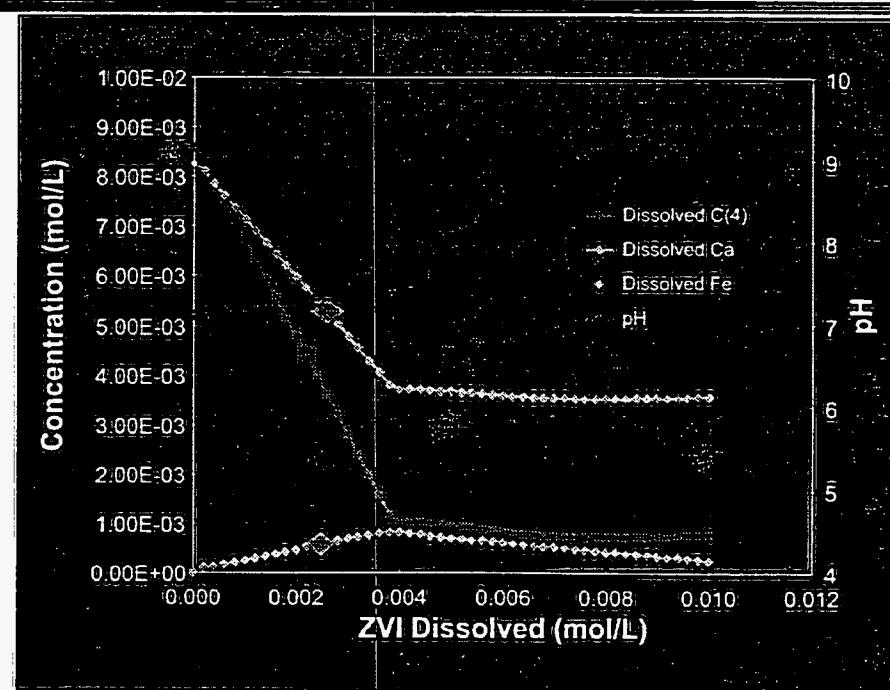


Figure 28. Calculated Reaction Path Chemistry as Groundwater Proceeds to Equilibrium with Zvi,  $\text{Fe}(\text{oh})_2$ , and Calcite. Large Symbols Indicate the Values That Were Observed the Column Effluents.

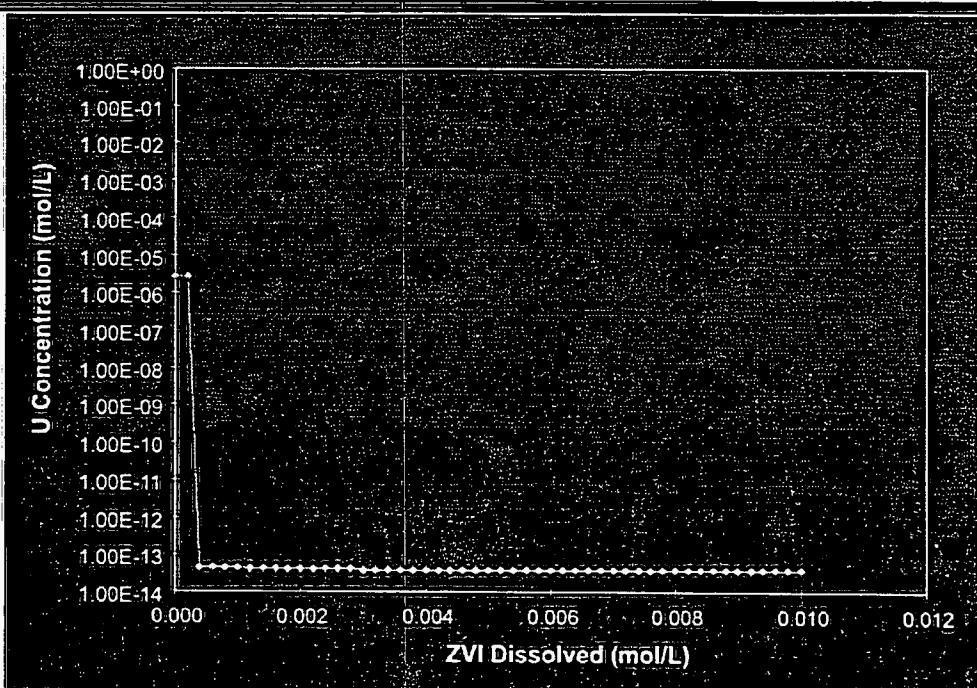
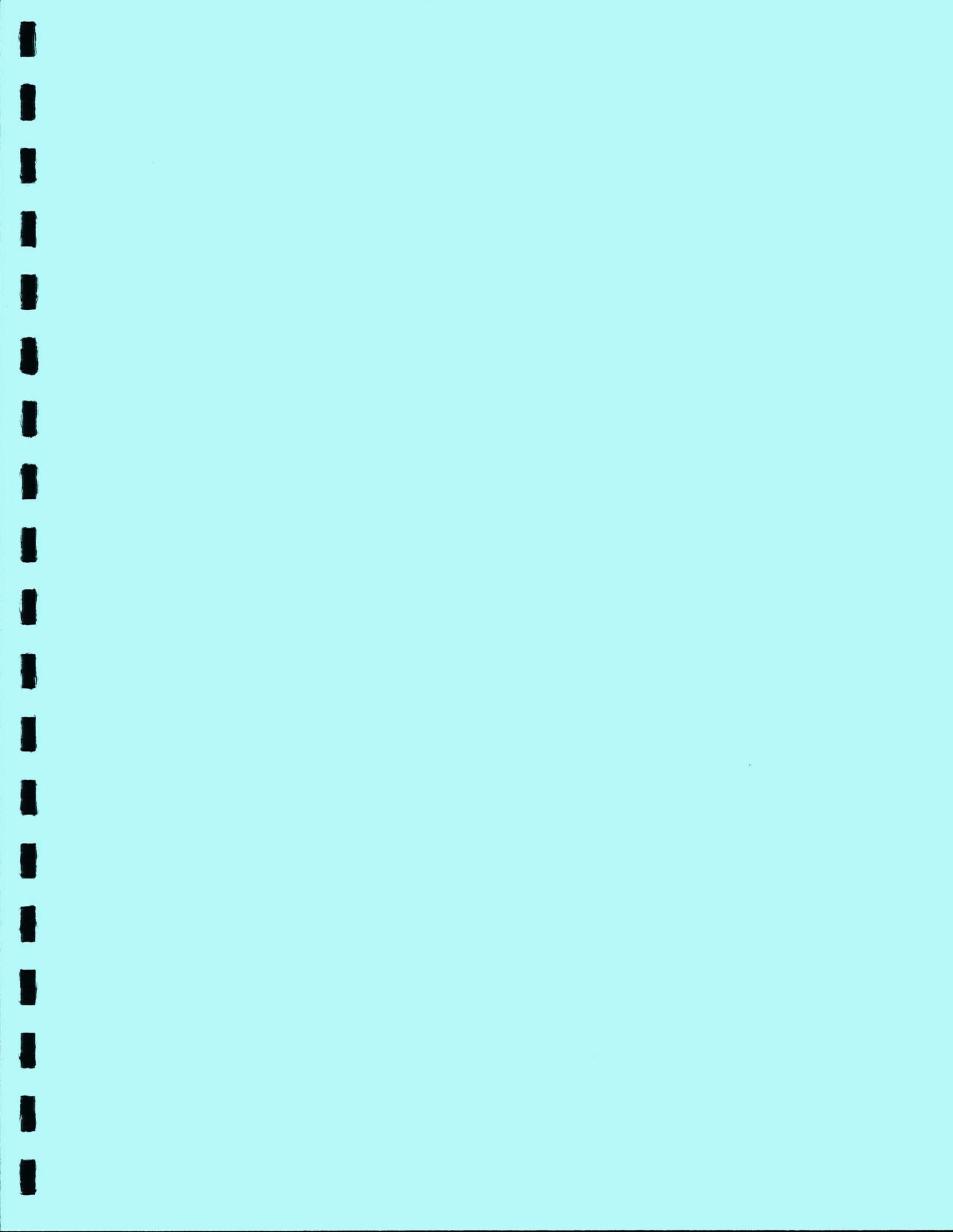


Figure 29. Calculated U Concentrations for Partial Equilibration of Groundwater with ZVI



**Appendix A  
Raw Data for Section IV**

Column 3: Peerless -8 +18, weight in column = 36.8 lbs

Porosity=52%, 1PV = 5.14 L

\* Elapsed Time since outflow (corrected for down time).

Sample	FIEL	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	ESL	ESL					
Date	Elaps	Pump	Actu	Period	Cum	Eff	Cum	E	Resid	Press	infl	effl	infl	effl	infl	effl	infl	effl	T Fe	Mn												
	Time*	Fl.	Rat	Fl.	R	Eff	Vol	Volume	Time	H2O	pH	pH	T	T	Alt	EC	EC	Eh	DO	DO	T Fe,f	T Fe,u	Fe+2,f	Fe+2,u	U	U	NO3	NO3	SO4	SO4	T Fe	Mn
	hours	mL/ml	mL/mi	L	L	PV	hr	in		deg	deg	deg	mg/L	mg/L	mg/cm	mv	mv	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
6/24/98	0	na	ne	0.0	0.0	0	na	na	6.74	6.76	13.6	27.2	410	195	2560	1730	183	-111	1.79	na	29.8	34	8	5.5	na	0.0002	na	na	53.7	0.88		
6/25/98	18	40	21.7	22.8	22.8	4	4.2	48.0	6.93	6.17	18.2	22.2	350	10	2560	2060	154	-39	2.8	1.55	7.400	14.400	6	6.2	na	na	na	na	63.8	0.88		
6/26/98	42	40	19.3	28.4	51.2	9	4.7	48.0	7.08	6.38	18.8	20.1	400	10	2560	2070	155	-42	3.11	2.08	10.000	12.000	4.400	4.500	0.675	0.0002	na	na	na	34.8	0.59	
6/29/98	120	40	19.3	90.3	141.5	26	4.7	na	7.16	6.74	25.8	19.5	435	35	2570	2110	140	-74	1.97	1.35	2.400	8.600	2.400	2.400	na	na	na	na	na	na		
7/1/98	162	40	16.2	40.8	182.3	34	5.6	49.0	7.18	7.19	18.3	16.2	370	92	2570	2200	140	-104	3.13	0.49	2.000	11.000	2.000	2.200	0.644	0.0002	na	na	na	na	na	na
7/2/98	185	80	36.0	49.7	231.9	43	2.5	48.0	7.12	7.32	18.6	18.5	375	155	2560	2310	170	-165	3.2	0.32	5.4	17.2	1	2.2	0.708	0.0003	na	na	na	na	24.8	0.22
7/5/98	210	80	36.0	52.9	284.9	52	2.5	50.0	7.08	7.09	18.8	20.3	410	120	2550	2200	162	-149	4.11	1.12	2.2	8.6	2.2	2.2	0.626	0.0001	na	na	na	na	17.2	0.17
7/6/98	302	80	82.7	346.1	631.0	116	1.4	48.0	6.74	7.26	13.7	21	330	155	2560	2080	193	-122	2.46	0.64	na	na	na	na	na	na	na	na	na	na		
7/6/98	327	80	73.6	110.4	741.4	137	1.2	47.0	na	na	16.4	na	na	na	na	na	na	na	na	na												
7/10/98	349	80	76.0	102.6	844.0	155	1.2	48.0	6.88	7.44	14	19.2	350	385	2570	2460	142	-195	1.47	0.24	15.2	24	3.8	4.2	0.677	0.0005	na	na	na	na	43.8	0.1
7/14/98	407	80	61.8	213.2	1057.2	195	1.5	47.0	7.15	7.18	18.4	23.8	330	270	2540	2400	197	-140	1.8	0.22	na	na	na	na	0.826	na	na	na	44.8	0.11		

END OF TEST

Column 4: Corcoran HSA -3 +30, weight in column = 44.2 lbs

Porosity=55%, 1PV = 5.43 L

\* Elapsed Time since outflow (corrected for down time).

Sample	FIEL	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	ESL	ESL					
Date	Elaps	Pump	Actu	Period	Cum	Eff	Cum	E	Resid	Press	infl	effl	infl	effl	infl	effl	infl	effl	T Fe	Mn												
	Time*	Fl.	Rat	Fl.	R	Eff	Vol	Volume	Time	H2O	pH	pH	T	T	Alt	EC	EC	Eh	DO	DO	T Fe,f	T Fe,u	Fe+2,f	Fe+2,u	U	U	NO3	NO3	SO4	SO4	T Fe	Mn
	hours	mL/ml	mL/mi	L	L	PV	hr	in		deg	deg	deg	mg/L	mg/L	mg/cm	mv	mv	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
6/24/98	0	na	ne	0.0	0.0	0	na	na	6.74	6.76	13.6	27.2	410	195	2560	1730	183	-111	1.79	na	29.8	34	8	5.5	na	0.0002	na	na	53.7	0.88		
6/25/98	18	40	21.7	22.8	22.8	4	4.2	48.0	6.93	6.17	18.2	22.2	350	10	2560	2060	154	-39	2.8	1.55	7.400	14.400	6	6.2	na	na	na	na	63.8	0.88		
6/26/98	42	40	19.3	28.4	51.2	9	4.7	48.0	7.08	6.38	18.8	20.1	400	10	2560	2070	155	-42	3.11	2.08	10.000	12.000	4.400	4.500	0.675	0.0002	na	na	na	na	34.8	0.59
6/29/98	120	40	19.3	90.3	141.5	26	4.7	na	7.16	6.74	25.8	19.5	435	35	2570	2110	140	-74	1.97	1.35	2.400	8.600	2.400	2.400	na	na	na	na	na	na		
7/1/98	162	40	16.2	40.8	182.3	34	5.6	49.0	7.18	7.19	18.3	16.2	370	92	2570	2200	140	-104	3.13	0.49	2.000	11.000	2.000	2.200	0.644	0.0002	na	na	na	na	na	na
7/2/98	185	80	36.0	49.7	231.9	43	2.5	48.0	7.12	7.32	18.6	18.5	375	155	2560	2310	170	-165	3.2	0.32	5.4	17.2	1	2.2	0.708	0.0003	na	na	na	na	24.8	0.22
7/5/98	210	80	36.0	52.9	284.9	52	2.5	50.0	7.08	7.09	18.8	20.3	410	120	2550	2200	162	-149	4.11	1.12	2.2	8.6	2.2	2.2	0.626	0.0001	na	na	na	na	17.2	0.17
7/6/98	302	80	82.7	346.1	631.0	116	1.4	48.0	6.74	7.26	13.7	21	330	155	2560	2080	193	-122	2.46	0.64	na	na	na	na	0.65	0.0001	na	na	na	na	na	na
7/6/98	327	80	73.6	110.4	741.4	137	1.2	47.0	na	na	16.4	na	na	na	na	na	na	na	na	na	na											
7/10/98	349	80	76.0	102.6	844.0	155	1.2	48.0	6.88	7.44	14	19.2	350	385	2570	2460	142	-195	1.47	0.24	15.2	24	3.8	4.2	0.677	0.0005	na	na	na	na	43.8	0.1
7/14/98	407	80	61.8	213.2	1057.2	195	1.5	47.0	7.15	7.18	18.4	23.8	330	270	2540	2400	197	-140	1.8	0.22	na	na	na	na	0.826	na	na	na	44.8	0.11		

END OF TEST

## FIELD COLUMNS: TDI PROJECT

Column Facts: Column Type = Acrylic 4-in diameter, 4 ft tall, Column volume (empty) = 9.88 L.

Fluid = Well 88-85.

na = not analyzed, bold type = below detection limit

Column 1: Master Builder GX027, weight in column = 40.7 lbs

Porosity=52%, 1PV = 5.14 L

\* Elapsed Time since outflow (corrected for down time).

Sample	FIEL	FIELD	FIEL	FIELD	FIEL	FIELD	FIEL	FIEL	FIEL	FIEL	FIEL	FIEL	FIEL	FIEL	FIEL	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	ESL	ESL					
Date	Elaps	Pump	Actu	Period	Cum E	Cum E	Resid	Press	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff				
	Time*	Fl	Rat	Fl.	R	Eff	Vol	Volume	Time	H2O	pH	pH	T	T	Alk	EC	EC	Eh	Eh	DO	DO	T Fe,f	T Fe,u	Fe+2,f	Fe+2,u	U	U	NO3	NO3	SO4	SO4	T Fe	Mn	
	hours	ml/min	ml/m	L	L	PV	hr	in	deg	deg	mg/L	mg/L	ms/cm	ms/c	mv	mv	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L		
6/18/98	0	na	na	0.0	0.0	0	na	50	6.59	11.2	14	28	430	175	na	na	161	74	2.29	6.15	na	na	na	na	0.827	0.0003	na	na	na	na	na	na		
6/19/98	18	40	20.0	21.0	21.0	4	4.3	48.0	6.76	6.7	17.4	17.2	430	55	na	na	4	-68	4.74	3.7	8.200	na	na	na	0.858	0.0002	na	na	na	na	na	na		
6/23/98	113	40	20.4	116.9	137.9	27	4.2	51.0	7.38	7.05	16.3	17.6	445	18	2620	2170	7	-87	4.57	2.01	5.800	na	2.200	na	0.851	0.0002	8.14	1.76	840	860	na	na		
6/24/98	138	40	18.0	26.5	164.4	32	4.8	na	6.74	6.74	13.6	22.4	410	28	2580	2150	183	-52	1.79	1.98	0.600	7.000	0.200	0.400	na	na	na	na	11.8	0.83	na	na		
6/25/98	162	40	21.7	31.2	195.6	38	3.9	44.0	6.93	6.54	18.2	21.2	350	10	2590	2130	154	-5	2.8	1.98	2.000	11.000	2.000	2.000	na	na	na	na	15.6	1.05	na	na		
6/26/98	186	40	20.5	29.5	225.1	44	4.2	48.0	7.08	6.48	18.8	19.4	400	10	2590	2140	155	-64	3.11	2.400	8.000	2.200	2.200	0.675	0.0002	na	na	na	na	12	0.87	na	na	
6/29/98	264	40	20.5	95.9	321.1	62	4.2	na	7.16	6.54	25.8	21.6	435	10	2570	2100	140	-25	1.97	1.94	1.800	5.600	1.800	2.000	na	na	na	na	na	na	na	na		
7/1/98	306	40	17.0	42.9	364.0	71	5.0	47.0	7.18	6.98	18.3	17.2	370	10	2570	2160	140	-79	3.13	0.8	5.800	9.600	3.500	3.500	0.644	0.0005	na	na	na	na	na	na	na	na
7/2/98	329	75	32.4	44.7	408.7	80	2.6	50.0	7.12	7.08	18.6	18.9	375	18	2560	2180	170	-127	3.2	0.49	10.000	16.400	3.800	3.800	0.708	0.0003	na	na	na	na	27.1	0.75	na	na
7/3/98	353	75	32.0	47.0	455.7	89	2.7	52.0	7.08	7.1	19.8	19.7	410	65	2550	2180	162	-150	4.11	0.4	7.600	9.800	3.800	3.200	0.626	0.0002	na	na	na	na	21.6	0.45	na	na
7/8/98	445	75	56.2	310.2	765.9	149	1.5	53.0	6.74	7.06	13.7	20.8	330	185	2580	2240	193	-129	2.46	0.79	na	na	0.65	0.0007	na	na	na	na	na	na	na	na		
7/9/98	470	75	67.0	100.5	866.4	169	1.3	57.0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na				
7/10/98	493	75	75.0	101.3	967.7	188	1.1	52.0	6.88	7.49	14	18.7	350	355	2570	2500	142	-213	1.47	0.23	25.6	31.2	4.8	5.4	0.677	0.0009	na	na	na	na	50.3	0.26	na	na
7/14/98	550	75	54.2	187.0	1154.7	225	1.6	51.0	7.15	7.17	18.4	23.4	330	280	2540	2390	197	-163	1.8	0.32	na	na	0.826	na	na	na	na	na	na	51	0.29	na	na	

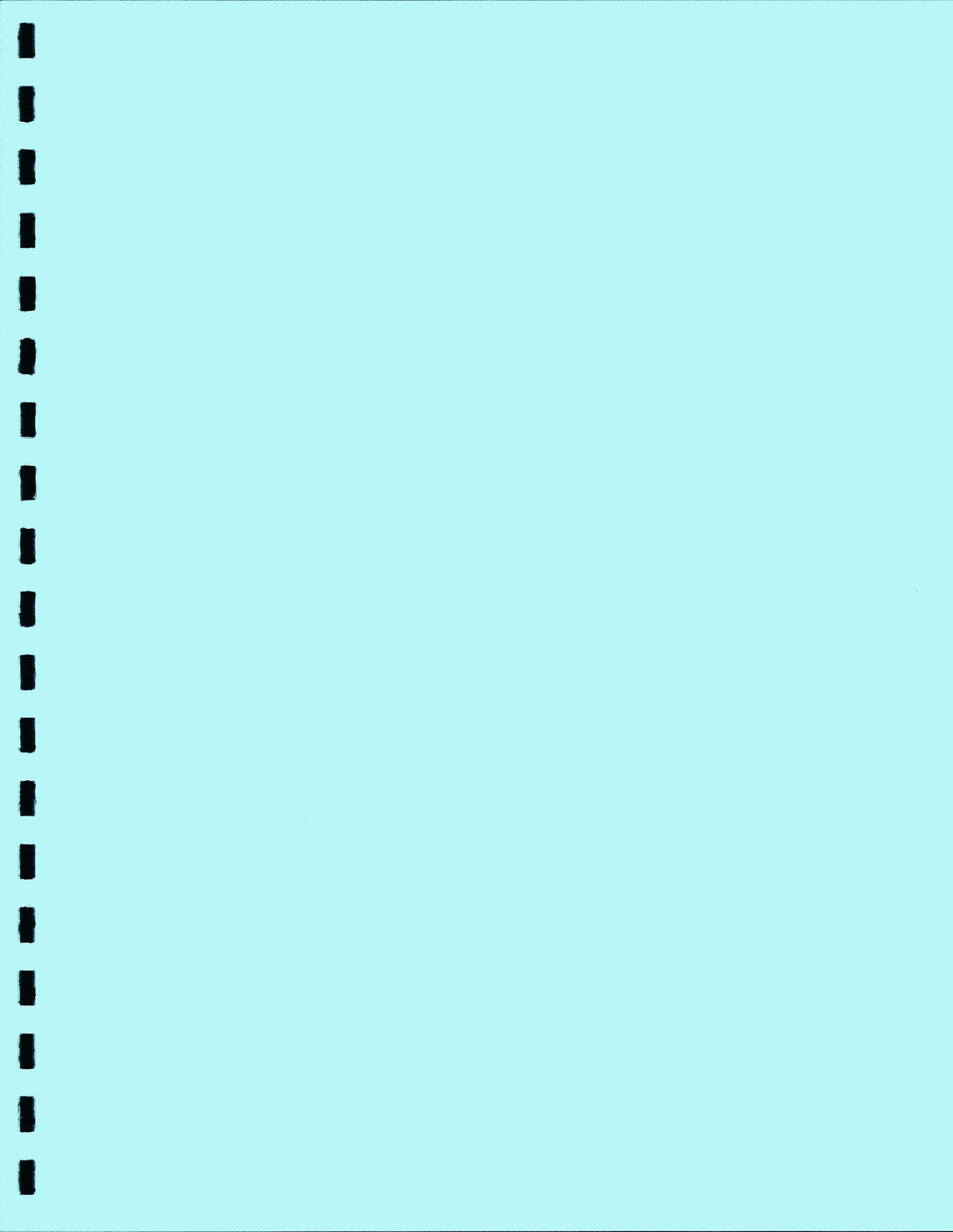
END OF TEST

Column 2.Connelly 1004, weight in column = .46.7 lbs

Porosity=52%, 1PV = 5.14 L

\* Elapsed Time since outflow (corrected for down time).

Sample	FIEL	FIELD	FIEL	FIELD	FIEL	FIELD	FIEL	FIEL	FIEL	FIEL	FIEL	FIEL	FIEL	FIEL	FIEL	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	ESL	ESL													
Date	Elaps	Pump	Actu	Period	Cum E	Cum E	Resid	Press	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff	infl	eff						
	Time*	Fl	Rat	Fl.	R	Eff	Vol	Volume	Time	H2O	pH	pH	T	T	Alk	EC	EC	Eh	Eh	DO	DO	T Fe,f	T Fe,u	Fe+2,f	Fe+2,u	U	U	NO3	NO3	SO4	SO4	T Fe	Mn			
	hours	ml/min	ml/m	L	L	PV	hr	in	deg	deg	mg/L	mg/L	ms/cm	ms/c	mv	mv	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L				
6/18/98	0	na	na	0.0	0.0	0	na	44	6.59	5.91	14	28.1	430	10	na	na	161	-13	2.29	6	na	4	na	na	0.827	0.0002	na	na	na	na	na	na				
6/19/98	18	40	20.0	21.0	21.0	4	4.3	48.0	6.76	8.45	16.3	17.9	445	77	2620	2210	7	-134	4.57	2.15	3.400	na	0.300	na	0.651	0.0001	8.14	0.88	840	840	na	na				
6/23/98	113	40	22.9	131.2	152.2	30	3.7	50.0	7.38	8.45	16.3	17.9	445	77	2620	2210	7	-134	4.57	2.15	3.400	na	0.300	na	0.651	0.0001	8.14	0.88	840	840	na	na				
6/24/98	138	40	21.0	30.8	183.1	36	4.1	na	6.74	8.39	13.8	22.4	410	85	2580	2210	183	-93	1.79	2.28	0.200	3.300	na	0.200	na	na	na	na	na	na	na	4.4	1.11			
6/25/98	162	40	23.3	33.8	216.6	42	3.7	48.0	6.93	8.43	18.2	21	350	160	2590	2230	154	-93	2.8	2.28	0.200	3.400	0.200	0.500	na	na	na	na	5.6	1.18	na	na				
6/26/98	186	40	21.8	31.1	247.7	48	4.0	51.0	7.08	7.42	18.8	19.6	400	100	2590	2180	155	-95	3.11	2	0.200	3.600	na	na	0.675	0.0004	na	na	na	na	6.8	1.14	na	na		
6/29/98	264	40	21.8	101.1	348.8	68	4.0	na	7.16	7.36	25.8	21.2	435	10	2570	2110	140	-69	1.97	2.2	0.200	3.200	0.200	0.200	na	na	na	na	na	na	na	na	na	na		
7/1/98	306	40	19.8	49.3	398.1	77	4.4	49.0	7.18	7.25	18.3	18.6	370	58	2570	2200	140	-76	3.13	0.93	0.200	4.200	0.280	0.200	0.644	0.0004	na	na	na	na	na	na	na	na	na	na
7/2/98	329	75	37.8	51.8	450.0	88	2.3	48.0	7.12	7.27	18.6	18.5	375	135	2580	2240	170	-140	3.2	0.37	4.000	12.000	1.600	2.000	0.708	0.0002	na	na	na	na	20	0.78	na	na	na	na
7/3/98	353	75	36.0	52.9	503.0	98	2.4	49.0	7.08	7.29	19.8	20	410	90	2550	2170	162	-151	4.11	1.62	1.000	4.800	0.800	1.200	0.626	0.0002	na	na	na	na	8.9	0.48	na	na	na	na
7/8/98	445	75	49.0	270.5	773.4	150	1.7	53.0	6.74	8.95	13.7	20.9	330	115	2580	2080	183	-124	2.46	0.83	na	na	na	na	0.65	0.0001	na	na	na	na	na	na	na	na	na	na
7/9/98	470	75	62.5	93.8	867.2	189	1.4	52.0	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na				
7/10/98	493	75	62.5	84.4	951.6	185	1.4	57.0	6.88	7.36	14	19	350	255	2570	2310	142	-162	1.47	0.49	9.6	18.4	3.2	3.8	0.677	0.0002	na	na	na	na	29.5	0.49	na	na	na	na



**Appendix B  
Raw Data for Section V**

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FIELD COLUMNS: TRI PROJECT

**Column Facts:** Column Type = Acrylic 4-in diameter, 4 ft tall; Column volume (empty) = 9.88 L

**Fluid = Well 88-86**

na = not analyzed, bold type = below detection limit

Column A (Also called Column 3): Peerless -8 +18, weight in column = 36.8 lbs

Porosity = 53% 1 PV = 5.14 l

Column B: Contain soil from the trench, packed while still wet (probable preferential flow). Abundant gravel. Removed gravel > 2". 42.3 lbs of soil in column.

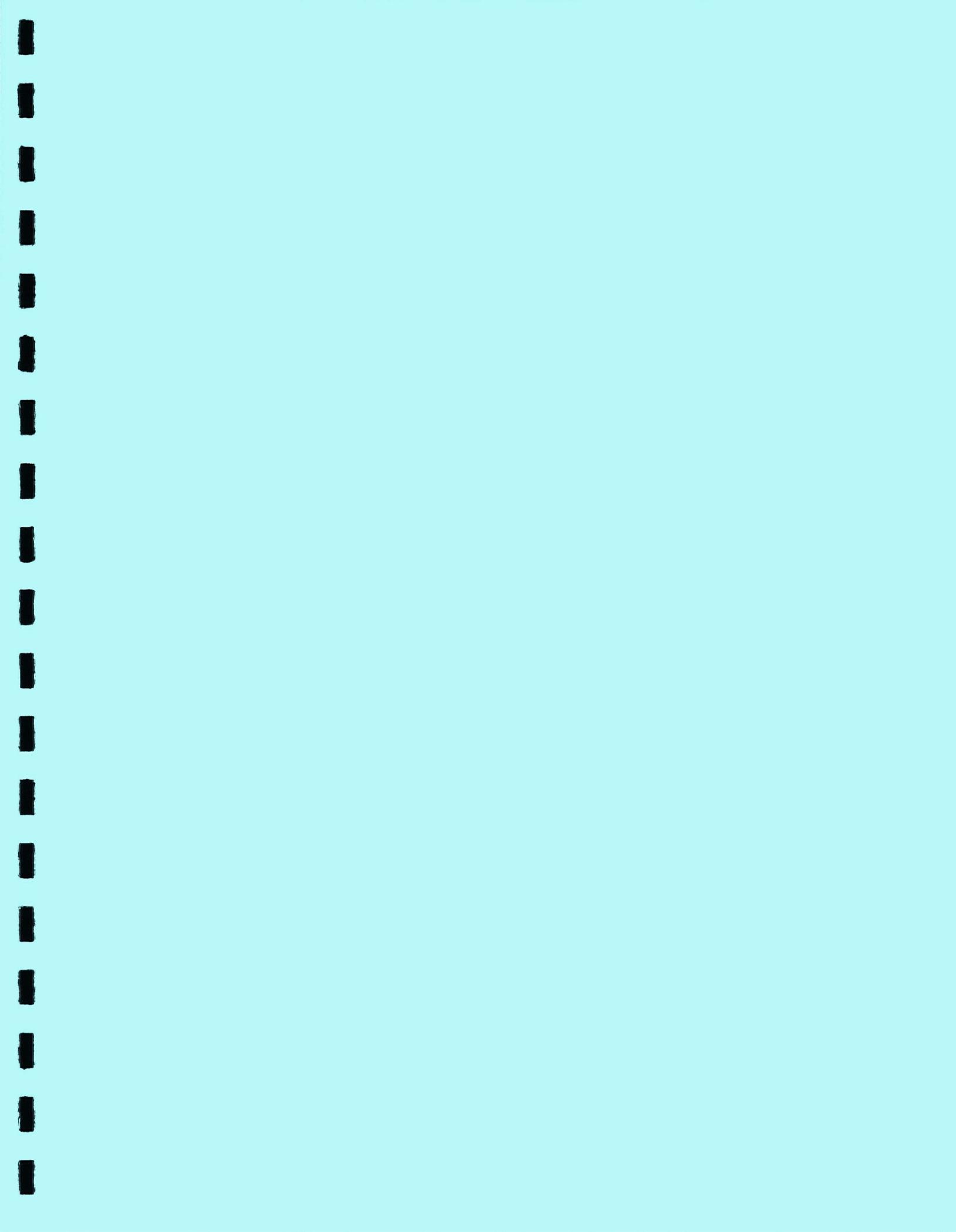
- Elapsed Time since initial outflow of Column A (corrected for down time).

Sample Date	FIELD Elaps	FIELD Pump	FIELD Actua	FIELD Period	FIELD Cum Eff	FIELD Cum E	FIELD Resid	FIELD Pressu	FIELD Pressu	FIELD infl	FIELD effl	FIELD effl	FIELD infl	FIELD DO	FIELD DO												
	Time* hours	Fl. mL/min	Rat. mL/m	Fl. L	Rat. PV	Fl. hr	Rat. in	Fl. H2O	Rat. H2O	pH	pH	pH	T	T	T	Alk.	Alk.	EC	EC	Eh.	Eh.	Eh.	Eh.	mv	mg/L		
COLUMN	A	A	A	A	A	A	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B			
7/20/98	426.5	0	0	0	1107	46	215	n/a	87	56	7.57	8.01	7.33	25.4	24.8	24.0	395	210	65	2510	1975	2130	34	-70	-10	4.67	3.2
7/21/98	443.5	80	62.5	63.75	1171	21	228	1.37	53	55	7.74	7.39	7.18	25.2	25.5	25.3	360	195	150	2600	2380	2380	-40	na	-54	na	na
7/22/98	467.5	80	64.6	93.02	1264	23	246	1.33	55	49	7.57	7.20	7.13	18.4	18.8	18.6	395	245	245	2600	2450	2460	-15	-126	-106	5.55	2.13
7/23/98	490	80	72.7	98.15	1362	38	265	1.18	57	49	7.48	7.33	7.22	20.9	21.6	21.0	370	285	280	2560	2460	2430	-9	-204	-161	5.08	1.18
7/24/98	515.5	80	61.5	94.1	1456	47	283	1.39	60	50	7.28	7.28	7.37	21.0	22.0	21.3	365	250	310	2560	2470	2470	-11	-208	-197	2.73	0.71
7/25/98	536.5	80	66.7	84.04	1540	52	300	1.28	70	43	7.24	7.35	7.20	20.2	20.3	20.0	440	305	245	2550	2460	2400	-25	-239	-166	3.8	0.84
7/26/98	561	40	33.3	48.95	1589	47	309	2.57	86	42	7.15	7.30	7.16	20.5	20.3	20.4	375	235	285	2530	2410	2390	-6	-178	-152	5.09	1
7/27/98	583	40	34.8	45.94	1635	4	318	2.46	98	41	7.24	7.16	7.15	20.9	20.4	20.2	430	265	245	2330	2190	2130	-13	-173	-167	5.3	1.21
7/28/98	609	40	32	49.92	1685	32	328	2.68	106	50	7.15	7.35	7.20	19.8	19.0	18.9	385	290	295	2520	2420	2410	125	-192	-143	5.15	0.98
7/30/98	666.5	40	31.5	108.7	1794	349	272	122	50	7.24	7.22	7.07	23.0	23.6	23.0	350	190	200	2500	2310	2270	-35	-165	-122	4.23	0.85	





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**Appendix C  
Raw Data for Section VI**

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FIELD COLUMNS: TDI PROJECT

Column Facts: Column Type = Acrylic 4-in diameter, 4 ft tall; Column volume (empty) = 9.88 L.

Fluid = Well 88-85.

na = not analyzed, bold type = below detection limit

Column A (Also called Column 3): Peerless -8 +18, weight in column = 38.8 lbs

Porosity=52%, 1PV = 5.14 L.

\* Elapsed Time since initial outflow of Column A (corrected for down time).

Column C is the aeration column. Contains 27.2 lbs of well sorted gravel. An aquarium pump was used to bubble air upwards from the bottom of Column C. Effluent from A was "dribbled" into the top and pumped out at the bottom.

Column D has 32.1 lbs of Bluff soil provided by Greg Smith. This was used to test another type of soil for removing Fe particles.

The trench soil was wet and probably did not represent the true subsurface porosity structure.

Mag. peroxide pellet was added for late 8/18 and 8/19

Sample Date	FIELD Elapsed Time*	FIELD Pump Fl. Rate mL/min	FIELD Actual Fl. Rate mL/min	FIELD Period Eff Vol	FIELD Cum Eff Volume	FIELD Resid PV	FIELD H2O Time hr	FIELD H2O in in	FIELD H2O in in	FIELD pH	FIELD pH	FIELD infl effl	FIELD infl effl	FIELD infl pH	FIELD T	FIELD T	FIELD T	FIELD Alk	FIELD Alk	FIELD Alk	FIELD mg/L a	FIELD mg/L a	FIELD mg/L a
COLUMN	A	A	A	A	A	A	A	A	A	A	A	A	A	A	deg C	deg C	deg C	deg C	deg C	mg/L a			
8/4/98	668.5	40	36.1	4.33	1798.33	350	2.37	80	na	58	7.01	7.20	7.24	7.73	20.2	24.1	24.2	23.4	380	130	60		
8/5/98	692.5	40	39.5	56.9	1855.2	361	2.17	72	na	57	6.89	7.25	7.94	7.41	24.1	29.6	29.5	29.2	385	255	175		
8/6/98	708.5	40	36.05	34.6	1889.8	368	2.38	106	na	56	7.04	7.42	7.97	7.80	23.1	21.0	20.9	20.4	390	310	190		
8/7/98	732.5	40	41.7	60.0	1949.9	379	2.05	126	na	59	7.10	7.20	7.78	7.66	23.5	21.7	22.4	22.4	365	240	150		
8/11/98	831	40	40	236.4	2186.3	425	2.14	114	na	52	7.05	7.38	na	7.12	20.7	21.8	na	21.8	380	210	na		
8/12/98	854.5	40	40	56.4	2242.7	436	2.14	114	na	61	7.10	7.20	na	6.99	21.9	25.8	na	24.5	385	230	na		
8/13/98	877.5	40	35.88	49.5	2292.2	446	2.39	104	na	47	7.45	7.17	na	7.02	23.1	21.8	na	22.2	275	220	na		
8/14/98	900.5	40	37.1	51.2	2343.4	456	2.31	110	na	62	7.07	7.36	na	7.13	21.7	18.2	na	17.9	295	225	na		
8/17/98	978	40	33.8	157.2	2500.5	486	2.53	128	na	72	7.58	7.06	na	7.00	25.5	27.0	na	28.1	330	210	na		
8/18/98	1002.5	40	31.2	45.9	2546.4	495	2.75	128	na	64	7.65	7.18	na	7.08	20.4	21.8	na	20.3	375	200	na		
8/18/98	1006	40	31.2	6.6	2553.0	497	2.75	na	na	na	na	na	na	na	na	na	na	na	na	na	na		
8/19/98	1020.5	40	27.9	24.3	2577.2	501	3.07	142	na	68	7.64	7.22	na	7.07	20.5	18.4	na	18.7	240	325	na		

	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD													
	effl	infl	effl	infl	effl	infl	effl	infl	effl	effl	effl	effl	effl	effl	effl	effl	effl	effl	effl	effl	effl	effl	effl	effl	
Alk	EC	EC	EC	EC	Eh	Eh	Eh	Eh	DO	DO	DO	DO	T Fe,f	T Fe,f	T Fe,u	T Fe,u	T Fe,u	Fe+2,f	Fe+2,f	Fe+2,f	Fe+2,f	Fe+2,u	Fe+2,u	Fe+2,u	Fe+2,u
mg/L	ms/cm	ms/cm	ms/cm	ms/cm	mv	mv	mv	mv	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
D	A	C	D	A	C	D	A	C	D	A	C	D	A	C	D	A	C	D	A	C	D	A	C		
230	2470	2180	2080	2720	147	-90	135	128	3.85	1.19	4.75	4.34	3	0.2	0.2	13.6	0.8	0.2	1.8	0.2	0.2	4.5	0.2		
190	2480	2430	2210	2190	124	-203	120	125	2.99	0.29	3.32	3.03	20.4	0.2	0.2	25.6	2.6	0.2	15	0.2	0.2	15	0.2		
150	2490	2430	2230	2200	129	-197	118	119	2.04	1.68	2.47	2.3	24	0.2	0.2	26.4	1.8	0.2	16	0.2	0.2	17	0.2		
140	2470	2360	2190	2180	125	-145	97	116	2.05	0.52	2.27	2.16	19.2	0.2	0.2	24.8	0.8	0.2	19	0.2	0.2	19	0.2		
220	2400	2310	na	2260	127	-168	na	-87	3.27	0.33	na	0.82	18.4	na	7	22.4	na	8	16	na	5.8	16	na		
230	2440	2350	na	2330	131	-171	na	-105	8.24	0.92	na	2.02	20	na	12	24	na	13.2	14	na	8.2	15	na		
215	2470	2330	na	2290	130	-147	na	-97	7.61	1.05	na	2.2	16.8	na	10.8	22	na	13	11	na	6.8	11.5	na		
265	2460	2430	na	2370	130	-188	na	-123	8.21	1.28	na	1.69	24	na	18.4	29.6	na	19.6	14	na	12	16	na		
180	2420	2270	na	2280	118	-133	na	-114	9.4	1.17	na	1.03	8.8	na	6.8	16.8	na	11.6	5.6	na	4.6	7.5	na		
215	2400	2310	na	2320	126	-129	na	-119	5.46	0.93	na	1.18	16	na	12.4	19.6	na	16.4	10	na	8.5	11	na		
na	na	na	na	na	na	na	na	na	na	na	na	2.85	18	na	0.3	19.6	na	0.5	10	na	0.2	11	na		
160	2400	2280	na	2280	47	-138	na	-86	6.86	1.14	na	2.04	14	na	5.8	19.6	na	5.8	10	na	5.5	11	na		







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#### **FIELD COLUMNS: TDI PROJECT**

**Column Facts:** Column Type = Acrylic 4-in diameter, 4 ft tall. Column volume (empty) = 9.88 L.

Fluid = Wall RR-85

PD = not analyzed; bold type = below detection limit

Column E: Peerless -8 +18, weight in column = 40.7 lbs

Porosity 52% 1PV = 5.14 l

\* Elapsed Time since outflow (corrected for down time).

Ports: Number is distance from bottom in inches: E1=2, E2=4, E3=6, E4=8, E5=13, E6=18, E7=23, E8=28, E9=33, E10=38, E11=43, EOOUT=outflow (-48 in)

## EFFLUENTS AND INFLUENTS FROM COLUMN E

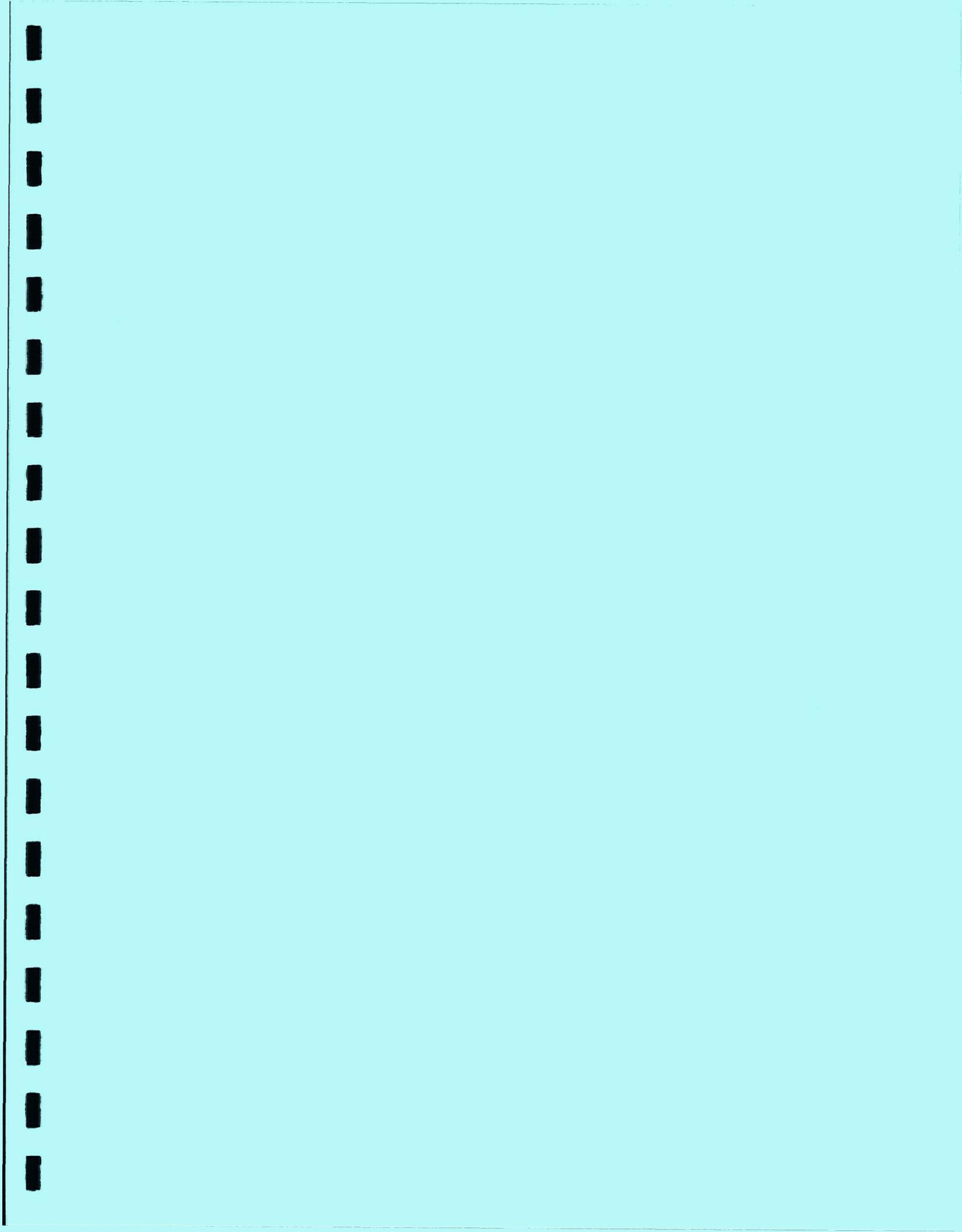
EFFECTS AND INCIDENTS FROM COLUMN E																										
Sample	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD	FIELD
Date	Elapsed	Pump	Actual	Period	Cum Eff	Cum Eff	Resid	Pressure	infl	infl	infl	infl	infl	infl	infl	infl	infl	infl	infl	infl	infl	infl	infl	infl	infl	infl
Time*	Fl Rate	Fl Rate	Eff Vol	Volume	Volume	Time	H2O	pH	pH	T	T	Alk	Alk	EC	EC	EC	Eh	Eh	DO	DO	T,Fe,I	T,Fe,u	Fe+2,I	Fe+2,u		
hours	mL/min	mL/min	L	L	PV	hr	in			deg C	deg C	mg/L	as mg/L	as ms/cm	ms/cm	mv	mv	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
8/12/98	0	40	na	0.0	0.0	0	na	43	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	
8/13/98	15	40	32.0	28.8	28.8	6	2.7	48.0	7.45	7.06	23.1	22	275	130	2470	2260	130	-110	7.61	1.33	3.000	20.000	1.4	2.5		
8/14/98	38	40	35.2	48.6	77.4	15	2.4	42.0	7.07	7.23	21.7	18.4	295	130	2460	2220	130	-76	8.21	2.07	4.400	15.200	1.400	1.600		
8/17/98	116	40	35.2	163.7	241.1	47	2.4	55.0	7.56	7.09	25.5	27.7	330	75	2420	2140	118	-77	9.4	1	0.800	8.000	0.500	0.600		
8/18/98	136	40	30.9	38.0	279.1	54	2.8	46.0	7.65	6.97	20.4	20.2	375	135	2400	2210	126	-91	5.46	1.02	6.800	14.800	3.000	4.250		

Sample	Port	Dist fro	FIELD	FIELD	FIELD	FIELD/E	FIELD	FIELD	ESL	ESL	CH LAB														
Date	Inlet	Cum	Eff	eff	eff	eff	eff	eff	T Fe	Mn	As	Ca	Cl	Fe	K	Mg									
		PV	deg C	mg/L	es	mg/cm	mv	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	ug/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
8/13/98	EOUT	48	6	7.06	22	130	2260	-110	1.33	3.000	20 000	1.400	2 500	0.001	na	na	na	1.84	na	na	na	na	na	na	na
	E11	43	6	7	na	6	0.003	na	na	na	na	na	na	na	na	na	na	na							
	E10	38	6	7	na	7	0.003	na	na	na	na	na	na	na	na	na	na	na							
	E9	33	6	7	na	7	0.002	na	na	na	na	na	na	na	na	na	na	na							
	E8	28	6	7	na	7	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E7	23	6	7	na	6	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E6	18	6	7	na	14	0.004	na	na	na	na	na	na	na	na	na	na	na							
	E5	13	6	7	na	17	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E4	8	6	7	na	21	0.002	na	na	na	na	na	na	na	na	na	na	na							
	E3	6	6	7	na	21.5	0.009	na	na	na	na	na	na	na	na	na	na	na							
	E2	4	6	7	na	18.5	0.002	na	na	na	na	na	na	na	na	na	na	na							
	E1	2	6	7	na	17.6	0.002	na	na	na	na	na	na	na	na	na	na	na							
	E0	0	6	7.45	23 1	275	2470	130	7.61	na	na	na	0.647	na	na	na	0.11	na	na	na	na	na	na	na	
8/14/98	EOUT	48	15	7.23	18.4	130	2220	-76	2.07	4.4	15.2	1.4	1.6	0.001	na	na	na	1.02	na	na	na	na	na	na	na
	E11	43	15	7	na	5.5	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E10	38	15	7	na	7	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E9	33	15	7	na	10	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E8	28	15	7	na	11	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E7	23	15	7	na	13	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E6	18	15	7	na	14	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E5	13	15	7	na	17	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E4	8	15	7	na	18	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E3	6	15	7	na	20	na	na	na	na	na	na	na	na	na	na	na	na							
	E2	4	15	7	na	23	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E1	2	15	7	na	22	0.003	na	na	na	na	na	na	na	na	na	na	na							
	E0	0	15	7.07	21 7	295	2460	130	8.21	na	na	na	0.506	na	na	na	0.12	na	na	na	na	na	na	na	
8/17/98	EOUT	48	47	7.09	27.7	75	2140	-77	1	0.8	8	0.5	0.6	0.001	na	na	na	0.64	na	na	na	na	na	na	na
	E11	43	47	7	na	5	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E10	38	47	7	na	6	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E9	33	47	7	na	7	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E8	28	47	7	na	11	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E7	23	47	7	na	13	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E6	18	47	7	na	15	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E5	13	47	7	na	17	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E4	8	47	7	na	18	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E3	6	47	7	na	16	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E2	4	47	7	na	17	0.001	na	na	na	na	na	na	na	na	na	na	na							
	E1	2	47	7	na	15	0.003	na	na	na	na	na	na	na	na	na	na	na							
	E0	0	47	7.56	25 5	330	2420	118	9.4	na	na	na	0.53	na	na	na	0.09	na	na	na	na	na	na	na	
8/18/98	EOUT	48	54	6.97	20 2	135	2210	-91	1.02	6.8	14.8	3	4.25	0.0013	na	na	na	0.55	3.3	194	145	17.5	11.8	82.3	
	E11	43	54	na	na	na	na	na	na	na	3.3	183	144	17.8	11.5	83									
	E10	38	54	na	na	na	na	na	na	na	3.3	203	148	19.6	11.7	82.7									
	E9	33	54	na	na	na	na	na	na	na	3.3	214	146	24.6	11.5	81.9									
	E8	28	54	na	na	na	na	na	na	na	3.3	238	147	31.1	11.6	82.2									
	E7	23	54	na	na	na	na	na	na	na	3.3	262	146	31.9	11.6	82.6									
	E6	18	54	na	na	na	na	na	na	na	3.3	286	147	22.9	11.6	83.6									
	E5	13	54	na	na	na	na	na	na	na	4.5	286	147	15.8	327	149	0.0578	11.7							
	E4	8	54	na	na	na	na	na	na	na	na	na	na	na	na	na	na								
	E3	6	54	na	na	na	na	na	na	na	na	na	na	na	na	na	na								
	E2	4	54	na	na	na	na	na	na	na	na	na	na	na	na	na	na								
	E1	2	54	na	na	na	na	na	na	na	na	na	na	na	na	na	na								
	E0	0	54	7.65	20.4	375	2400	126	5.46	na	na	na	0.605	na	na	na	0.1	15.8	327	149	0.0578	11.7	84.1		

## 8/18/98 FOR PLOTTING

Date	Sample Port	CH LAB																Dist from inlet
		effl	effl	effl	effl	effl	effl	effl										
		As	Ca	Cl	Fe	K	Mg	Mn	Mo	Na	NO3	Se	SO4	U	V			
ug/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	ug/L	mg/L	ug/L	mg/L	ug/L	mg/L	ug/L	ug/L	ug/L	In		
8/18/98	EOUT	3.3	194	145	17.5	11.8	82.3	0.555	14.5	251	0.0191	2.2	950	1.1	1.1	48		
	E11	3.3	193	144	17.8	11.5	83	0.523	16.8	253	0.0124	2.2	946	1.1	1.1	43		
	E9	3.3	203	148	19.6	11.7	82.7	0.492	15.7	251	0.011	2.2	961	1.1	1.1	33		
	E7	3.3	214	146	24.6	11.5	81.9	0.512	15.3	246	0.0287	2.2	959	1.1	1.1	23		
	E5	3.3	238	147	31.1	11.6	82.2	0.443	16.5	249	0.0217	2.2	963	1.1	1.1	13		
	E3	3.3	262	146	31.9	11.6	82.8	0.306	29.9	251	2.39	2.2	967	1.1	1.1	6		
	E1	4.5	286	147	22.9	11.6	83.6	0.209	46.1	251	6.42	5.6	975	4.2	1.4	2		
	E0	15.8	327	149	0.0579	11.7	84.1	0.0708	62.5	252	12.8	8.5	978	627	452	0		





**Appendix D**  
**Raw Data for Section IX**

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| CH LAB |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| infl   | effl   |
| NO3    | NO3    | 210Pb  | 210Pb  | Se     | Se     | SO4    | SO4    | U      | U      | V      | V      |        |        |
| mg/L   | mg/L   | pCi/L  | pCi/L  | ug/L   | ug/L   | mg/L   | mg/L   | ug/L   | ug/L   | ug/L   | ug/L   |        |        |
| na     |        |        |
| na     |        |        |
| na     |        |        |
| na     |        |        |
| 12.8   | 0.0191 | na     | na     | 8.5    | 2.2    | 978    | 950    | 627    | 1.1    | 452    | 1.1    |        |        |